CHALMERS
UNIVERSITY OF TECHNOLOGY

Comparative research in Room Acoustics Simulation Software

Master's thesis in Master Programme Sound and Vibration

NEZA KRAVANJA

Department of Architecture and Civil Engineering
Division of Applied Acoustics
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2018

Master's thesis BOMX02-16-27

Comparative research in Room Acoustics Simulation Software

NEZA KRAVANJA

CHALMERS
UNIVERSITY OF TECHNOLOGY

Department of Architecture and Civil Engineering
Division of Applied Acoustics
Room Acoustics Research Group
Chalmers University of Technology
Gothenburg, Sweden 2018

Comparative research in Room Acoustics Simulation Software
NEZA KRAVANJA

Supervisor: Jan-Inge Gustafsson, Akustikon, Norconsult AB
Examiner: Wolfgang Kropp, Department of Architecture and Civil Engineering, Division of Applied Acoustics

Master's Thesis BOMX02-16-27
Department of Architecture and Civil Engineering
Division of Applied Acoustics
Room Acoustics Research Group
Chalmers University of Technology
SE-412 96 Gothenburg

Tel. +46 31 772 1000

Reproservice / Department of Architecture and Civil Engineering
Gothenburg, Sweden 2018

Master's thesis in Master Programme Sound and Vibration
NEZA KRAVANJA
Department of Architecture and Civil Engineering
Chalmers University of Technology

Abstract

In rooms for speech and music, the suitable sound environment is one of the most important components of space design. Room Acoustics Simulation Software is often used to predict sound conditions in a non-existing room. However, the design process presents many unknowns such as the room geometry, settings, and materials. All these uncertainties might cause an error in the prediction.

The simplifications of complex sound behavior in Geometrical Acoustics are another source of error. The understanding and evaluation of expected inaccuracy give the user insight and the ability to critically assess the simulation results.

In this research, three software packages, widely used among the practitioners in the field, are compared: Odeon Auditorium and CATT-Acoustics v8.0 and v9.0.

Through a model 'tuning' process, a relationship between reality and simulations was established, enabling the comparison between the two.
Simulated Room Acoustics Parameter values at specific receiver positions are compared to measured values in existing large rooms: Grosse Muzikverein in Vienna, Malmö Live concert hall in Malmö and Norconsult AB Canteen in Göteborg.

The models with different level of detail and varying types of audience area geometrical simplifications were used to determine the accuracy and limitations of the software predictions.

Keywords: room acoustics, simulation, software, acoustic parameters, Odeon Auditorium, CATT-Acoustics.

Acknowledgements

First and foremost my greatest thanks go to Jan-Inge Gustafsson. He was not just a supervisor, but he introduced me to his world full of curiosity and passion for acoustics.

I would like to thank Wolfgang Kropp, Mendel Kleiner and other professors and researchers for the guidance throughout the years.

Last but not least, I would like to thank my family and my friends. I could not have done it without your support and encouragement.

Neza Kravanja, Gothenburg, May 2016

Contents

List of Figures

List of Tables

1. Introduction

1.1 Purpose

During the design process of a room, which requires special acoustical considerations, many unknowns are present such as the geometry, settings, and materials. All these uncertainties might cause an error in prediction of the sound space environment.

Another source or error is the simplification of sound propagation in Geometrical Acoustics, widely used to simulate acoustic conditions in rooms. The understanding and evaluation of this error give the user insight and the ability to critically assess the results obtained by a Room Acoustics Simulation Software.

1.2 Objective

The objective of the research was to evaluate the ability of the software to predict the acoustic environment as a reflective portrait of reality.

In research three Room Acoustics Simulation Software were compared: Odeon Auditorium and CATT-Acoustics versions 8.0 and 9.0, as commonly used by the practitioners in the field.

1.2.1 Proposed approach

Simulated Room Acoustics Parameter values in specific receiver positions are compared to measured values in existing large rooms: Grosse Muzikverein in Vienna, Malmö Live concert hall in Malmö and Norconsult AB Canteen in Göteborg.

Different levels of detail in geometrical models and varying types of audience modeling are also used to determine the accuracy and limitations of the software predictions.

2. Background

2.1 Sound environment

The sound environment is one of the most important components of design in rooms for speech and music. Acoustic conditions have to be carefully planned and optimized for a specific use. Sound energy emitted in a room decays and eventually dies out. The process is influenced by geometry and material and treatment of the surfaces in the room. Measuring or simulating the energy decay in a specific position enables to describe and evaluate the room properties using calculated Room Acoustics RA parameters. Tables 2.1 and 2.2 include an overview of the parameters, their definition and calculation method.

Table 2.1: Definition of RA parameters [1].

RA parameter	Definition
Sound Strength G [dB]	Sound pressure level at the specific receiver position deducted by the sound pressure level relative to free-field at 10m from the source.
Early Decay Time EDT [s]	Decay time calculated for first 10 dB drop (evaluation decay range 0 to $-10dB$) and multiplied by 6.
Reverberation Time T30 [s]	Time required for the reverberant sound to decay for 30dB (evaluation decay range -5 to $-35dB$).
Clarity C80 [dB]	Ratio between early energy (time range 0 to $80ms$) and late, reverberant energy (time range $80ms$ to ∞).
Definition D50 [%]	Ratio between early, direct energy (time range 0 to $50ms$) and total energy (time range $0ms$ to ∞).
Centre Time TS [ms]	Time of the centre of gravity of the squared Impulse Response.
Lateral Fraction LF [%]	Ratio of early energy (5 to $80ms$) weighted by cos^2 (lateral angle) to total energy (time range $0ms$ to ∞).
Lateral Fraction LFC [%]	Ratio of early energy (5 to $80ms$) weighted by cos (lateral angle) to total energy (time range $0ms$ to ∞).
Inter Aural Cross Correlation IACC	Ratio between energy at the two ear positions (time range 0 to $1000ms$). $IACC_{Early}$ (0 to $80ms$) and $IACC_{Late}$ (80 to $1000ms$).

Table 2.2: Calculation method for RA parameters [1].

RA parameter	Formula	
G	$G = 10\log\frac{\int_0^\infty p^2(t)dt}{\int_0^\infty p^2_{dir10m}(t)dt}$	[dB]
EDT	$EDT = 10\log\frac{\int_t^\infty p^2(t)dt}{\int_0^\infty p^2(t)dt}$	[s]
T30	$T30 = 10\log\frac{\int_t^\infty p^2(t)dt}{\int_0^\infty p^2(t)dt}$	[s]
C80	$C80 = 10\log\frac{\int_0^{80ms} p^2(t)dt}{\int_{80ms}^\infty p^2(t)dt}$	[dB]
D50	$D50 = 10\log\frac{\int_0^{50ms} p^2(t)dt}{\int_0^\infty p^2(t)dt}$	[%]
TS	$TS = \frac{\int_0^\infty tp^2(t)dt}{\int_0^\infty p^2(t)dt}1000$	[ms]
LF	$LF = \frac{\int_{5ms}^{80ms} p_8^2(t)dt}{\int_{0ms}^{80ms} p^2(t)dt}$	[%]
LFC	$LFC = \frac{\int_{5ms}^{80ms} \lvert p_8(t)p(t)\rvert dt}{\int_{0ms}^{80ms} p^2(t)dt}$	[%]
IACC	$IACC_{t1,t2} = \mid IACF_{t1,t2}(\tau) \mid_{max}$ $for - 1ms < \tau < +1ms$	

With the aim to find a correlation between measured and perceived acoustic qualities, RA parameters were linked to musical properties, and Just Noticeable Difference JND values were derived from laboratory listening experiments in Psychoacoustics. The correlations are shown in table 2.3.

Table 2.3: RA parameters, perception and JND [1][2].

RA parameter		JND
G	*Loudness*	1dB
EDT	*Reverberance*	5%
T30	*Reverberance*	5%
C80	*Clarity*	1dB
D50		0.05
TS		10ms
LF	*Spaciousness*	0.05
LFC	*Spaciousness*	0.05
IACC	*Spaciousness, Envelopment*	0.075

Some of the physical measures can be directly related to perceived acoustic qualities of a room; Intimacy with Initial Time-Delay Gap ITDG, reverberance with Reverberation Time RT, warmth with low frequency Reverberation Time RT and Bass Ratio BR and loudness with Sound Level G.

2.2 Geometrical Acoustics

Geometrical Acoustics GA is a simplification of sound propagation applied to sound behaviour in rooms. With the assumption that air is homogeneous and isotropic and that the sound wave has a front described as a surface (with a curvature greatly larger than the wavelength and only slightly varying amplitude) and according to Fermat's principle, determining that sound propagates by the shortest path between source and receiver, it enables a simplification of sound propagation with rays. In practice, large room volumes are needed or careful consideration of frequency range where assumptions are applicable [3]. The objective is to simulate the Impulse Response in a specific position in a room, composed by direct sound and reflections which are at first treated individually and later overlapped and summed up. The simulated energy decay in a room is used to calculate RA parameters [4].

2.2.1 Image-Source Method

Image-Source Method ISM is a geometrical principle that describes the deterministic specular reflection by mirroring the source over an infinitive reflective surface. The model of the room is a collection of all valid Image Sources IS for a specific Source-Receiver position and their corresponding secondary sources on the reflecting surface which radiate energy according to the surface absorption properties as shown in figure 2.1.

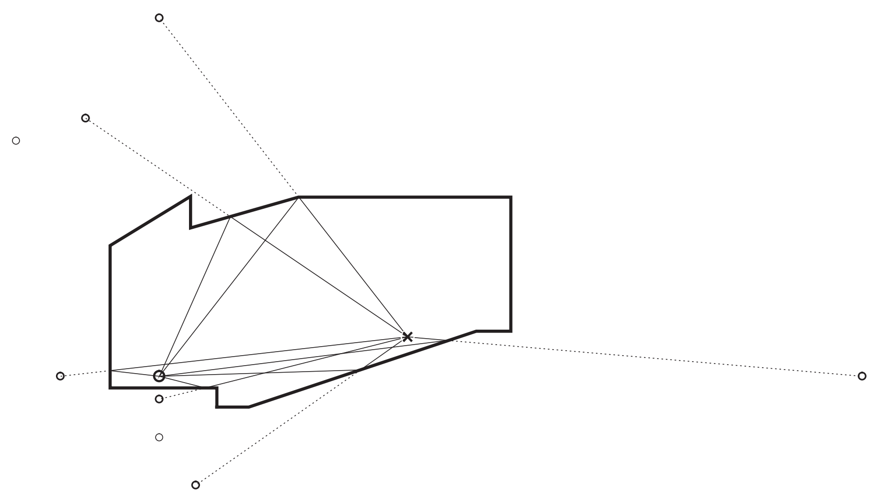

Figure 2.1: ISM model of a room with source and receiver position, valid and invalid first order IS and constructed first specular reflections.

The ISM principle can easily be applied to rectangular and geometrically simple rooms with rigid boundaries, but it is hardly applicable to more complex room shapes. A source is in theory mirrored over infinite surfaces. When it is mirrored over a big number of small finite surfaces, many false IS are detected. A geometrical obstacle interrupting the path between the source and the receiver or a reflection path out of the surface boundaries result in omitted rays and cause errors in the sound propagation simulation [3].

2.2.2 Ray-Tracing

Ray-Tracing RT is a stochastic method. It consists of emitting a number of particles from a source in various directions and tracing their movement and energy. When a particle/ray hits a surface, it is reflected in a newly defined direction, and it has its energy reduced according to the absorption properties of the reflective surface. To obtain the energy in a specific position in a room, the receiver has to be defined as a volume or a surface, summing up the 'caught' rays. Due to the randomization of the ray directions a high number of rays is needed to prevent the fluctuation in the results [3].

Due to the volumetric definition of a receiver, invalid rays for a specific listener position can be detected, especially when the receiving volume intersects the room geometry.

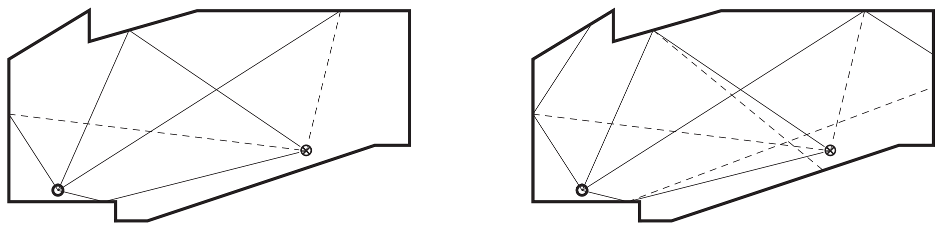

Figure 2.2: Diffuse reflections in RT can be modelled by directing a ray according to scattering coefficient (left) or splitting the ray in specular and diffusive components (right).

The main advantage of RT method is the easy application of diffusion. A ray has a specular and a diffuse component according to the defined ratio assigned to the reflective surface by a scattering coefficient. The application of the diffuse reflections can be implemented in two ways. First, by defining the random direction angle, if the scattering coefficient of the reflective surface is larger than a randomly generated number and otherwise reflecting the ray secularly, or second, splitting the ray into two components, one reflected secularly and the other in a random direction defined by Lambert´s distribution. In latter case, the ray number is exponentially increasing throughout the simulation, resulting in prolonged computation time, that is why the direction angle that represents a vector sum of two components is sometimes used [4]. Two different applications are shown in figure 2.2.

2.2.3 Beam- or Cone-Tracing

Easier detection of a ray by a point-like receiver can be achieved by adding a volumetric component to the ray. The method is called Beam-Tracing BT if the rays are substituted by pyramidal beams or Cone-Tracing CT if they are substituted by cones. BT or CT can be implemented as an extension of the basic principles of ISM or RT methods [4].

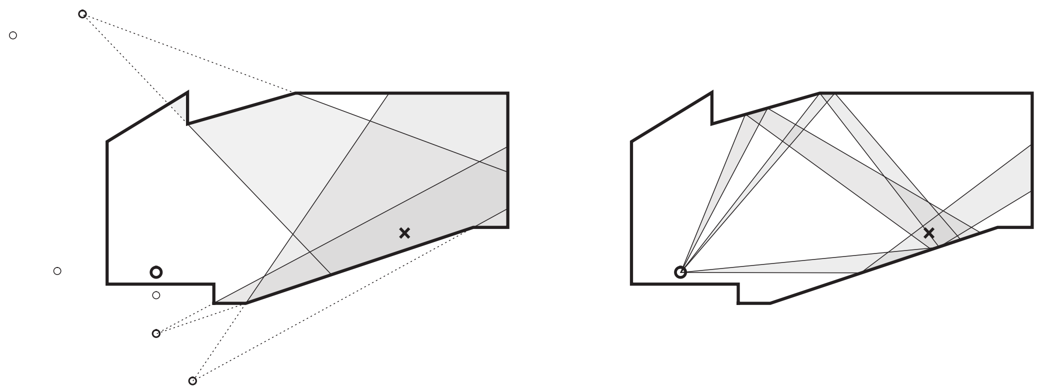

Figure 2.3: CT as an extension of ISM (left) or RT (right).

In the process of BT or CT as an extension of ISM, IS are created the same as in ISM and beams or cones by the edges of geometry as shown in figure 2.3 (left). The beam is then reflected only against the surfaces that are partially inside the beam; the others are neglected.

In the process of BT or CT as an extension of RT, a sphere around the source is divided into equal areas, that are geometrically extracted into beams or cones as shown in figure 2.3 (right). In the first method, the sphere is easily divided without any area overlapping defining every triangular beam with three rays. As a result, the method is very exact. The second method is computationally less demanding, while cones are just defined by one ray, but a correction factor has to be applied due to a volume overlapping. Geometry also affects the number of beams or cones; if the beam or cone is reflected from the edge of two surfaces, this results in split-up [5].

2.2.4 Acousticsl Radiosity

Acoustical Radiosity AR [6] is a surface-based GA modeling method with assumptions that reflections are ideally diffuse with the direction determined by Lambert´s law. The assumption is less regulative than the assumption of specular reflections in ISM and more applicable to the late part of the echogram.

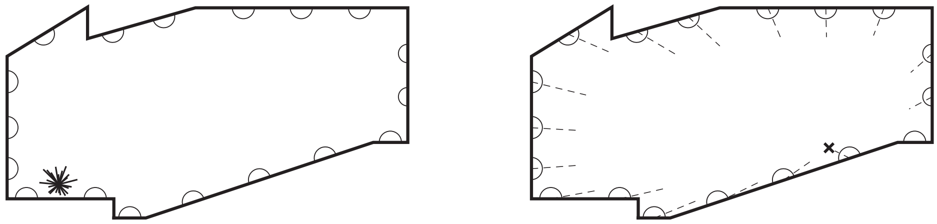

Figure 2.4: Two steps of AR simulations. Receiver independent part (left) and energy sum-up at receiver position (right).

In the AR pre-process the room geometry is described using radiating surfaces with radiating energy which is angle independent and consequently independent on the position of the source or receiver. After the pre-processing, the energy at the receiver position is summed-up. The process is fast, enabling the fast prediction even with moving the receiver. Two steps of the AR process are shown in figure 2.4.

The main disadvantage of the method is its incompatibility to include edge diffraction, which has to be added using numerically calculated approximations [4][6].

2.2.5 Hybrid methods

With an aim to combine the advantages of different basic GA methods hybrid methods were developed.
Path-based simulation of early reflections results in efficient accuracy in the first part of the echogram, surface-based simulation of late reflections enables a faster application of diffusivity and lower computation time. The transition point between two methods is usually predefined to an explicit reflection order, but in the calculation process, the methods are overlapping depending on the room geometry; the last early reflections arrive later than first late reflections [7].

2.3 Past research in RA simulation software

In the 1995, 2000 and 2005 three comparative researches in RA Computer Simulations software called Round Robins were carried out by the Acoustics and Dynamics Department of Physikalisch-Technische Bundesanstalt in Braunschweig. The aim was to test the reliability and reproducibility of simulation software used in RA. Participants (software developers and its users), were asked to model the rooms of interest, simulate the acoustic environment and provide the results in terms of 8-9 RA parameter values. The simulated results were later compared to the measurement results undertaken in the existing rooms. In the first phase, the material properties were estimated by the participants using provided documentation to evaluate the impact of their skill and experience on the result, in a second phase the absorption and diffusion coefficients were provided by the study coordinator [12],[13],[14].

The results of the First Round Robin have shown that the reliability of the result cannot be directly related to the basic GA method (ISM, RT, CT, BT or hybrid models). Only three of the tested software provided results of higher accuracy. Their common denominator was the implementation of diffusive reflections [12].

In the Second Round Robin, the possibility of using a geometrical model with material absorption in diffusion properties was provided by the coordinator. This significantly reduced the impact of users' experience on the accuracy of the result and enabled more detailed research. The study has shown that while the results were more reliable due to the consistent geometry, more substantial errors have occurred in lower frequency bands and some particular parameters such as D50 [13].

In the Third Round Robin the room of interest was smaller, it included adjustable acoustics and significant diffusive elements. Due to the small room size the distances between source and receivers positions were significantly shorter. The study has shown a good correspondence of measured and simulated results and the validation of simulations in small rooms. The larger deviations were observed in parameters T30 and EDT by the software packages without angular absorption implementation. An investigation in more complex geometry and comparison of auralizations with recorded sounds were highlighted as aspirations for the future research [14].

The three Round Robin researches have shown that RA Computer Simulation Software yields reliable results when absorption and scattering coefficients are carefully estimated. The expected deviation from the measured data can be of the same magnitude as the measurement uncertainty or JND.

3. Theory

In the comparative research, three software for RA simulations were compared. Odeon Auditorium version 13 released in 2015, designed by company Odeon from Denmark and CATT-Acoustics, developed by Bengt-Inge Dalenbäck in Sweden, versions v8.0i, released in 2009 and v9.0b, released in 2011.

All of the software use hybrid GA methods as a basic algorithm. They implement diffusive reflections, and their previous versions performed well in the Round Robin research.

The main differences among the software are basic GA methods, their implementation and transitioning and application of diffuse reflections.

3.1 Direct sound

When a sound source emits an impulse, a sound wave propagates away from the source in all directions with the power defined by the source directivity. The direct sound will be, because of the shortest propagating distance, the first and the strongest sound detected by the receiver at any position.

Since human perception of the sound is binaural, the sound incidence gives the listener a clear picture of the spatial position of the source. Localization is, according to the Haas effect determined by the first arriving wave even when the direct sound path is blocked by the barrier or masked by another louder sound.

The simulation of direct sound is unambiguous if the path between the source and the receiver is clear and uninterrupted, if not, as it can occur for receivers on balconies the software uses different techniques to predict the timing and the energy of the first component of the echogram.

3.1.1 Odeon

When the direct sound path is interrupted by the geometry, the additional, fragmented path around the interrupting object is created.

First, the ray is sent from the source towards the receiver and the point of incidence is registered. Then the process is repeated in the opposite direction - from the receiver to the source. If the points of incidence can be linked with one sub-path, this path is used for further calculation as a direct sound path. If not, the direct sound will not be detected, and the direct sound component will not be present in the echogram [8].

3.1.2 CATT-Acoustics v8.0 and v9.0

When the direct sound path is interrupted, this will reflect in no direct sound component in the echogram. The calculation of acoustic parameters will detect the start point, where the direct sound would have arrived if the path had been clear, taking into account the timing, but not the energy [9][10].

3.2 Reflections

When the sound wave is reflected from an infinite and perfectly smooth surface, the reflection is specular. In reality, no surface meets the criteria and the reflection on any rough material or surface boundary cause the redirection of the incident sound energy outside the specular direction. The result is diffused sound energy according to equation 3.1, where α is the absorption coefficient and δ the diffusion coefficient [11].

$$\alpha_{[absorbed]} + \delta(1-\alpha)_{[diffused]} + (1-\delta)(1-\alpha)_{[specular]} = 1 \tag{3.1}$$

The diffused energy is a result of two physical processes: scattering, which occurs due to the roughness of the material and the diffraction, due to the change in geometry, where edge diffraction is the most significant component. Both are frequency and angle of incidence dependent and the direction-wise spread in a half-sphere above the surface.

In GA methods, scattering and diffraction are implemented separately. Scattering is evaluated as material properties by the scattering coefficient. Diffraction can be entirely executed or defined by the user as an additional scattering to the surface around the edge. The summed diffuse energy is represented as a ray split-up component and implemented by the randomization of the reflection angle.

3.2.1 Scattering

Scattering coefficient s describes the ratio between the reflected sound power in non-specular directions and the total reflected sound power from an infinite surface. It is evaluated in a range between 0 and 1, where $s = 0$ describes purely specular reflection and $s = 1$ ideally scattered sound [7].

3.2.1.1 Odeon scattering implementation

As a part of the Reflection Based Scattering Coefficient, surface scattering s_s is defined at middle frequency, around 707 Hz. To implement scattering frequency dependency, s_s is extrapolated using extrapolation curves for different frequency bands.

The values at mid-frequencies are easily estimated by the visual appearance of a surface, where values from 0.005-0.05m are suggested for smooth materials, 0.05-0.03m for surfaces with a geometry variation resembling brick wall and 0.4-0.5m for rough building structures with a depth of 0.3-0.5m [8].

3.2.1.2 CATT-Acoustics scattering implementation

In CATT-Acoustics scattering can be applied to surfaces in two ways: the explicit values of surface scattering $s_{surface}$ for six octave-bands from 125Hz to 4kHz or by defining an estimate, where a numerical value represents the roughness scale in meters d and is extracted using the equation 3.2.

$$s = 50\sqrt{\frac{d}{\lambda}} \tag{3.2}$$

Spectral scattering coefficient values can also be imported from the CATT-Acoustic library with a collection of measured scattering data for different materials [9][10].

3.2.2 Diffraction

Diffraction is caused by bending of sound waves around edges. It occurs due to finite room boundaries, obstacles in a room, or changes in material causing a change in acoustic impedance.

3.2.2.1 Odeon diffraction implementation

Diffraction as a part of the Reflection Based Scattering Coefficient [8] is estimated using Rindel's theory taking into account the dimensions of the surface, the angle of incidence and the reflected path lengths. If the dimensions of a panel are $l \times w$, the frequency response of the panel can be divided in three main parts defined by an upper limiting frequency f_w and a lower limiting frequency f_l. At frequencies higher than f_w (calculated as shown in equation 3.3), the response is flat, as if the panel was infinitely large. Below the f_w, the response falls by 3dB per octave. At f_l (calculated as shown in equation 3.4) and below the fall off-is by 6dB.

$$f_w = \frac{ca^\star}{2(w\cos\theta)^2} \tag{3.3}$$

$$f_l = \frac{ca^\star}{2l^2} \tag{3.4}$$

$$a^\star = \frac{d_{inc}d_{refl}}{2(d_{inc} + d_{refl})} \tag{3.5}$$

The characteristic distance $a^\star$ calculated as shown in equation 3.5 indicates that a short distance between source and receiver and the surface, may provide specular reflection even if the surface is small, while a long distance will result in scattered sound.

The attenuation factors K_w and K_l calculated as shown in equations 3.6 and 3.7 estimate the fraction of energy that is reflected specularly.

$$K_w = \begin{cases} 1 & for \quad f > f_w \\ \frac{f}{f_w} & for \quad f \leq f_w \end{cases} \tag{3.6}$$

$$K_l = \begin{cases} 1 & for \quad f > f_l \\ \frac{f}{f_l} & for \quad f \leq f_l \end{cases} \tag{3.7}$$

Assuming that the energy not reflected specularly is diffracted, the scattering coefficient due to diffraction s_d can be calculated as shown in equation 3.8.

$$s_d = 1 - K_w K_l (1 - s_e) \tag{3.8}$$

Where s due to the edge s_e is 0.5 and becomes 0 if the reflection point is more than one wavelength away from the edge, as shown in equation 3.9.

$$s_e = \begin{cases} 0 & for \quad d_{edge}\cos\theta \geq \frac{c}{f} \\ 0.5(1 - \frac{d_{edge}\cos\theta f}{c}) & for \quad d_{edge}\cos\theta < \frac{c}{f} \end{cases} \tag{3.9}$$

Many variables in the estimation of s_d are known only when the calculation is already ongoing. Narrow angles of incidence reflect in high scattering, while parallel walls in low scattering and consequently flutter echo.

3.2.2.2 CATT-Acoustics diffraction implementation

Diffraction is implemented as an additional scattering to the edge area of the surfaces and is applied when the reflection point is less than 1/4 of a wavelength from the edge. The edge scattering coefficient s_{edge} is 0.5 and unified for all frequency bands since the frequency dependency is implemented by the edge width [9][10].

3.2.3 Diffuse reflection implementation

3.2.3.1 Odeon diffusion implementation

Reflection Based Scattering Coefficient s_r combines the surface roughness scattering coefficient s_s and the scattering coefficient due to the diffraction s_d and is calculated for every surface using equation 3.10.

$$s_r = 1 - (1 - s_d)(1 - s_s) \tag{3.10}$$

The diffuse reflection direction is defined by Oblique Lambert's law, designed to prevent perfectly diffuse last reflection. If the s_r is 1, the orientation is of traditional Lambert source, if it is less and not 0, the orientation is determined by using Vector Based Scattering Coefficient with scaled directivity pattern to account for the shadow zone created by the Lambert source rotation [8].

3.2.3.2 CATT-Acoustics diffusion implementation

Specular reflection in first order is reduced by the scattering coefficient of the edge s_{edge}. In higher orders it is calculated taking into account the surface scattering coefficient $s_{surface}$, the surface area $S_{surface}$ and the area of edge diffraction S_{edge} as shown in equation 3.11.

$$s_{effective} = s_{surface} + s_{edge}S_{edge}/S_{surface} \tag{3.11}$$

If $s_{effective}$ is higher than 1, the surface edge is treated as perfectly diffusive [9][10].

3.3 GA method

3.3.1 Odeon

Odeon Auditorium 13 implements a hybrid method of ISM and RT for early reflections and AR for late reflections. The transition is defined as Transition Order TO as shown in figure 3.1.

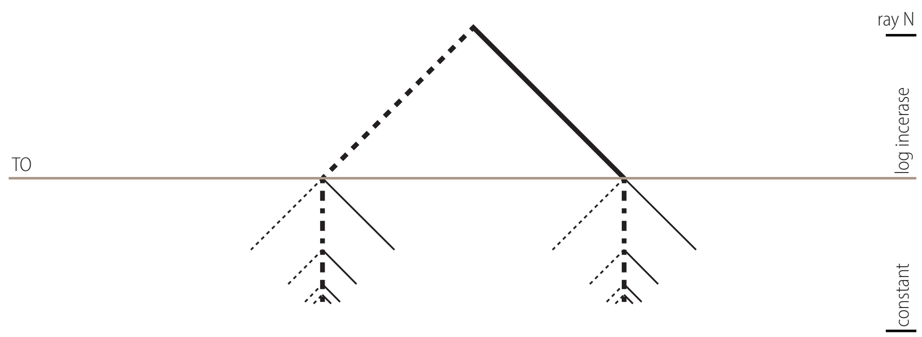

Figure 3.1: Ray reflection tree up to 5^{th} reflection order in Odeon, TO 1.*

The simulation starts with the receiver independent pre-process consisting of two parts. In the first part, the set of valid IS up to TO is generated. In the second part, the number of rays is released from the source and reflected according to the surface size and roughness, generating the secondary sources in the reflection points. The reflection direction is defined by the vector sum of a specular reflection and diffused reflection (randomized angle defined by Oblique Lambert distribution), keeping the number of rays constant.

In the receiver dependent part of the process, the reflections relevant for the specific position are 'collected' and the impulse responses are generated.

TO can be defined by the user according to the room properties. Higher TO in orthogonal and geometrically correct rooms with hard materials will result in highly controlled first part of the pre-process [8].

3.3.2 CATT-Acoustics v8.0

Randomized Tail-corrected Cone-tracing RTC [9] is based on RT method, supplementing rays with cones. Due to the method characteristic cone volume overlapping explained in 2.2.3, the late part of the echogram has to be reduced by the 'tail' correction.

Ray reflection is shown in figure 3.2. The direct sound, first and second order specular and first order diffuse reflections are angle predetermined.

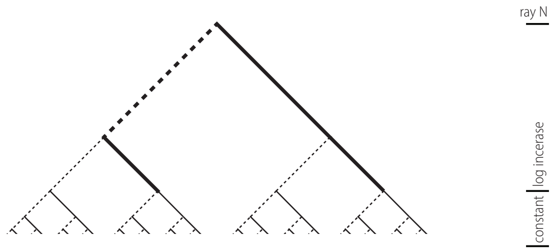

Figure 3.2: Ray reflection tree up to 5^{th} reflection order in CATT-Acoustics 8.0.*

3.3.3 CATT-Acoustics v9.0

The Universal Cone-Tracker TUCT [10] implements CT in three different algorithms handling specular and diffuse reflections equally to avoid needed 'tail' correction in RTC.

In Algorithm 1 first reflections are predetermined with ray-split-up in specular and diffuse up to max split order (from 0 to 2) as shown in figure 3.3. In orders higher than max split-order the direction is determined by the scattering coefficient. Algorithm 1 is used to accurately simulate sound propagation in closed rooms with equally distributed absorption.

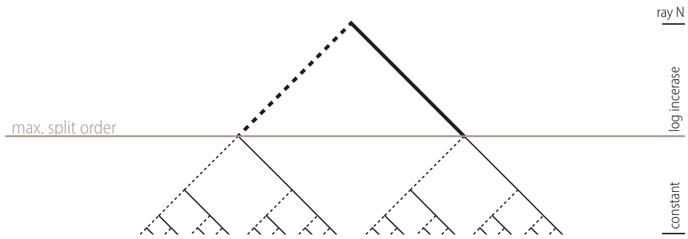

Figure 3.3: Ray reflection tree up to 5^{th} reflection order in CATT-Acoustics 9.0, Algorithm 1, max split-order 1.*

As shown in figure 3.4, Algorithm 2 uses predetermined ray split-up for all reflection orders of Specular-Specular and Specular-Diffuse nature. It is used to simulate sound in partly open or geometrically regular rooms with strong flutter echoes and uneven absorption.

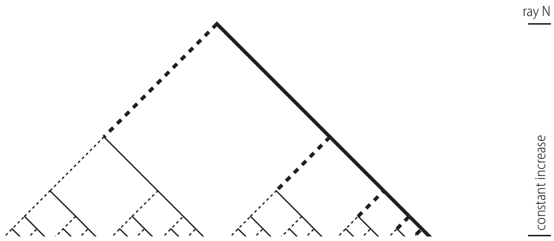

Figure 3.4: Ray reflection tree up to 5^{th} reflection order in CATT-Acoustics 9.0, Algorithm 2.*

Algorithm 3 uses predetermined ray-split for reflections of Specular, Specular-Diffuse, Specular-Diffuse-Specular, Specular-Diffuse-Diffuse, Diffuse-Specular and Diffuse-Diffuse nature as shown in figure 3.5. It is used to simulate sound propagation in open spaces.

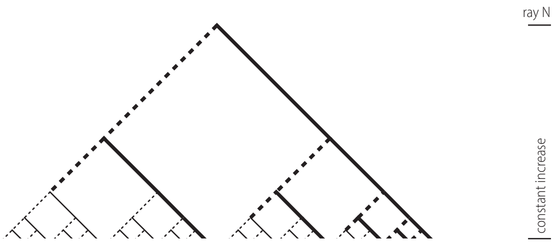

Figure 3.5: Ray reflection tree up to 5^{th} reflection order in CATT-Acoustics 9.0, Algorithm 3.*

* *Every fork represents a ray reflection, solid lines represent specular reflection paths and dashed lines diffuse reflection paths, thick lines present deterministic ray split-up paths and thin lines only random ray reflection.*

4. Method

The measurements of Impulse Responses IR in defined positions were undertaken in three large rooms, Grosse Muzikverein in Vienna, concert hall Malmö Live in Malmö and Norconsult AB Canteen in Göteborg.

IRs in the same positions were simulated using RA Simulation Software eliminating the major sources of error. Room geometrical models of interest were modeled in independent software, and the material absorption properties and its application were consistent. Due to different diffusion implementation, characteristic to particular software, small changes in input had to be made, expecting to lead to deviations in the results.

The simulation models were 'tuned' to measurements applying small changes in audience area absorption to achieve the same predicted average values of T30.

Than other measured and simulated parameter values at specific positions were compared.

4.1 Measurements

All the measurements of IRs were undertaken in unoccupied rooms using a maximum-length-sequence system software called WinMLS which calculates RA parameters in accordance with ISO 3382. Temperature and humidity were recorded and reproduced in simulations.

4.1.1 Grosse Muzikverein, Vienna

The measurements in concert hall Grosse Muzikverein in Vienna was made on the 5^{th} of May 2011 by Akustikon, Norconsult AB. 3 source positions on the stage and 31 receiver positions in the hall were used: 13 stalls, 4 loges, 5 balcony loges, 6 balcony and 3 gallery positions. IRs were measured with omnidirectional and figure-of-eight microphones.

Coordinates of source and receiver measurement positions can be seen in tables A.1 and A.2.

4.1.2 Malmö Live concert hall, Malmö

The results of the official measurements by Gade & Mortensen Akustik A/S on the 28^{th} of April 2015 after Malmö Live concert hall completion, were used. 2 source positions on the stage and 17 receiver positions in the hall were measured, using omnidirectional and figure-of-eight microphones: 6 stalls, 4 first balcony, 4 second balcony and 3 third balcony positions.

Coordinates of source and receiver measurement positions can be seen in tables B.1 and B.2.

4.1.3 Norconsult AB Canteen, Göteborg

Measurements in Norconsult AB Canteen in Göteborg was made on the 23^{rd} of March 2016 using 2 source positions and 10 receiver positions. Only omnidirectional microphones were used since the room does not have a set orientation.

Coordinates of source and receiver measurement positions can be seen in tables C.1 and C.2.

4.2 Computer models

4.2.1 Geometry

Room geometry was modeled using Google Sketchup 8 and imported into different RA Simulation Software. Consistency in geometry models significantly decreased any cause of error due to the geometry input.

L. M. Wang in her research [15] introduces the characterization of computer model level of detail using the ratio between the number of surfaces and the volume. The models in her research are less detailed (simple approximations of rooms with six surfaces), and consequently, the ratio numbers much lower. The modified categorization used in the comparative research is shown in table 4.1.

Table 4.1: Level of detail in computer model as introduced by L. M. Wang (left) and modified for the comparative research (right).

N of S/V [m^{-3}]	Level of detail	N of S/V [m^{-3}]
0.003 to 0.01	*Low*	0.03 to 0.08
0.01 to 0.015	*Medium*	0.08 to 0.2
0.015 to 0.03	*High*	0.2 to 0.6

4.2.1.1 Grosse Muzikverein, Vienna

Table 4.2 shows the categorization of three geometrical models of Grosse Muzikverein according to the level of detail.

Table 4.2: Level of detail in computer model of Grosse Muzzikverein.

Model	N of Surfaces	Volume [m^3]	N of S/V [m^{-3}]	Level of detail
1	457	13900	0.033	*Low*
2	1170	13900	0.084	*Medium*
3	7415	13900	0.534	*High*

The model with High level of detail was produced based on the output of high-resolution 3D laser-scanner. The high accuracy of the method enables the small objects and intricate details to be scanned and precisely reproduced in geometrical computer model based on existing characteristics of the room.

The computer models of Grosse Muzikverein can be seen in figures A.1, A.2 and A.3.

4.2.1.2 Malmö Live concert hall, Malmö

The categorization of geometrical models of Malmö Live concert hall according to the level of detail is shown in table 4.3.

Table 4.3: Level of detail in computer model of Malmö Live concert hall.

Model	N of Surfaces	Volume $[m^3]$	N of S/V $[m^{-3}]$	Level of detail
1	1310	21655	0.061	*Low*
2	3292	21655	0.152	*Medium*

The computer models of Malmö Live concert hall can be seen in figures B.1 and B.2.

4.2.1.3 Norconsult AB Canteen, Göteborg

Table 4.4 shows the categorization of two models of Norconsult AB Canteen according to the level of detail. Ratio numbers are much higher due to the small room volume.

Table 4.4: Level of detail in computer model of Norconsult AB Canteen.

Model	N of Surfaces	Volume $[m^3]$	N of S/V $[m^{-3}]$	Level of detail
1	238	547	0.435	*High*
2	2265	547	4.141	*Very High*

The computer models of Norconsult AB Canteen can be seen in figures C.1 and C.2.

4.2.2 Absorption coefficients

Simulating the sound environment of an existing room has an advantage. Absorption coefficients of the installed materials are included in technical reports. The values are obtained by measurements in laboratory, and only small fluctuation can be expected when mounted in-situ.

For materials without measured absorption data, the coefficients were assigned using Akustikon, Norconsult AB library according to material visual assessment. One of such was audience area, which is one of the most complex in terms of absorption and scattering and due to its proportion has a significant effect on the sound environment.

The material absorption coefficients were consistent in all of the RA Simulation Software, and the models with different levels of detail were assessed according to the area-weighted mean absorption coefficient. Values were kept in the deviation range of 2%.

4.2.3 Scattering coefficients

In his research [16], M. J. Howarth describes inaccurate diffuse coefficient specification as one of the most common and relevant sources of error in RA Simulations, due to the fact that there is no standard method for measuring diffusion properties of a finite surface. Visual judgement is a conventional technique of evaluating, only dividing the surfaces in 'rough' and 'smooth'.

Past research [17] has also proven that the scattering coefficients between 10% and 70% best describe reality and lower and higher values should be avoided. On the contrary, the software manuals [8][9][10] accept the values out of the proven range. The software manuals were in this research referred on as reliable resources.

The assigned scattering coefficients were comparable, but not identical since the implementation of scattering differs among the software.

Audience area scattering coefficient was evaluated around 60% at mid-frequencies and was applied as 0.6 in Odeon (at 707Hz) and < 40 50 60 80 80 80 > in CATT-Acoustics (in octave-bands from 63Hz to 4kHz). The area has high absorption properties, and the importance of the precision is significantly reduced.

In models with a lower level of detail, coefficients values were in average 10% to 30% higher in mid-frequencies, taking into account the geometry simplification. How the change was applied to the highly diffusive walls, and ceiling in Malmö Live concert hall can be seen in table 4.5.

Table 4.5: Scattering coefficient change in two models of Malmö Live concert hall.

Detail Level	Odeon	CATT-Acoustics
Low	0.55	< 50 60 70 90 90 90 >
Medium	0.05	< 20 17 15 13 11 10 >

Edge diffraction in CATT-Acoustics was assigned to the balcony fronts and under balcony surfaces, reflectors, chandeliers and some small décor surfaces in the concert halls and the furniture in the canteen.

4.3 Model 'tuning'

A relationship between the measured and the simulated data had to be established, to enable the comparison between the two. The process is called model 'tuning'.

T30 was chosen as a 'tuning' criterion. The parameter describes the time required for the reverberant sound to decay for 30dB (from -5dB to -35dB) and is commonly used to describe the sound quality in a room. It is calculated a shown in table 2.2 and can be measured with high precision.

The simulated average values of T30 were compared to the measured values, and with small adjustments in the absorption coefficient of the audience area changed to achieve good coherence.

In every room for music or speech, a large area is dedicated to the audience. Occupied or unoccupied with upholstered seating, it is difficult to assess it's absorption and diffusion properties. That is why it's absorption, and diffusion coefficients were chosen as the 'tuning' variables.

Two different methods of the 'tuning' process were considered:

Method 1 - To 'tune' average T30 obtained by every software and every model with a different level of detail. This method results in different material properties input for every model. The comparison of the results highlights the deviation that occurs due to the method implementation specific to every software. The method is, on the other hand, very time-consuming. Some software/model with high level of detail combinations have the computation time up to 72 hours, and the precise 'tuning' process takes a number of re-runs.

Method 2 - To 'tune' average T30 obtained by one of the software and one model with a specific level of detail and keep the material properties input constant in every other software and model. The method introduces additional sources of error with the decisions made in the process; defining the 'tuning' software and 'tuning' model. The comparison of the results emphasizes the deviation that occurs due to the change in the model detailing and the method.

Only small differences were expected due to the method implementation and the time frame of the research was limited. Consequently, the second method was chosen.

4.3.1 'Tuning' process

1 - The 'tuning' model was imported in CATT-Acoustics v8.0.

2 - The material properties were assigned to the surfaces using Akustikon, Norconsult AB library, and software material library.

3 - The simulated average T30 in octave-bands from 125 to 4kHz was compared to

the measured.

4 - Small changes in absorption coefficients in octave-bands from 125 to 4kHz of the audience area were applied to achieve good coherence of the measured and the simulated results.

In figure 4.1, the change in average T30 by applying the change in the absorption coefficients of the audience area from <33 39 46 50 51 56> to <26 28 42 46 54 59> in frequency bands from 125Hz to 4kHz can be seen. The values represent absorption properties of the wooden and thinly upholstered seating in Grosse Muzikverein, Vienna, and are, after the 'tuning' process not deviating significantly from the values from the material library.

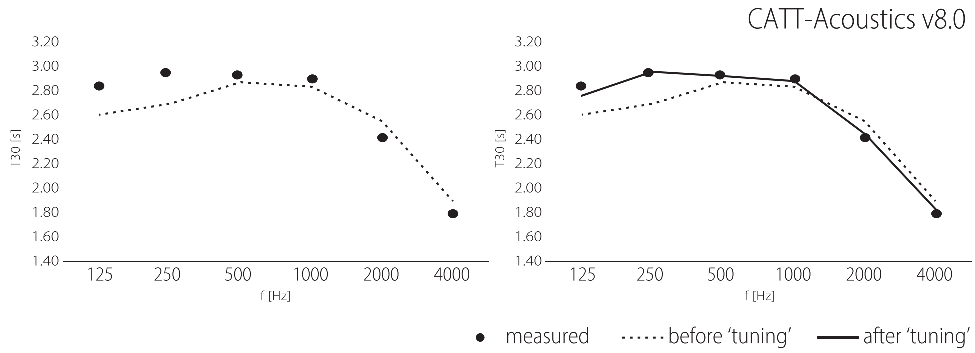

Figure 4.1: Measured and simulated average values of T30[s] in octave bands[Hz] obtained by CATT-Acoustics v8.0 and the model with Medium level of detail of Grosse Muzikverein, Vienna, before and after the 'tuning' process.

5 - The 'tuned' audience area absorption properties were applied to the models in two other software.

6 - Scattering coefficients in Odeon were adjusted according to the change in software scattering implementation as shown in figure 4.2.

7 - The material properties were kept consistent in the models with Low and High level of detail and only changes in scattering coefficients according to geometry change were applied.

The 'tuning' model in Grosse Muzikverein was the model with Medium level of detail, in Malmö Live concert hall the model with Low level of detail and in Norconsult AB canteen the model with High level of detail.

The absorption properties of the hard materials in Norconsult AB canteen were evaluated from visual judgment and assigned using the material library. In the 'tuning' process only scattering coefficients were adjusted.

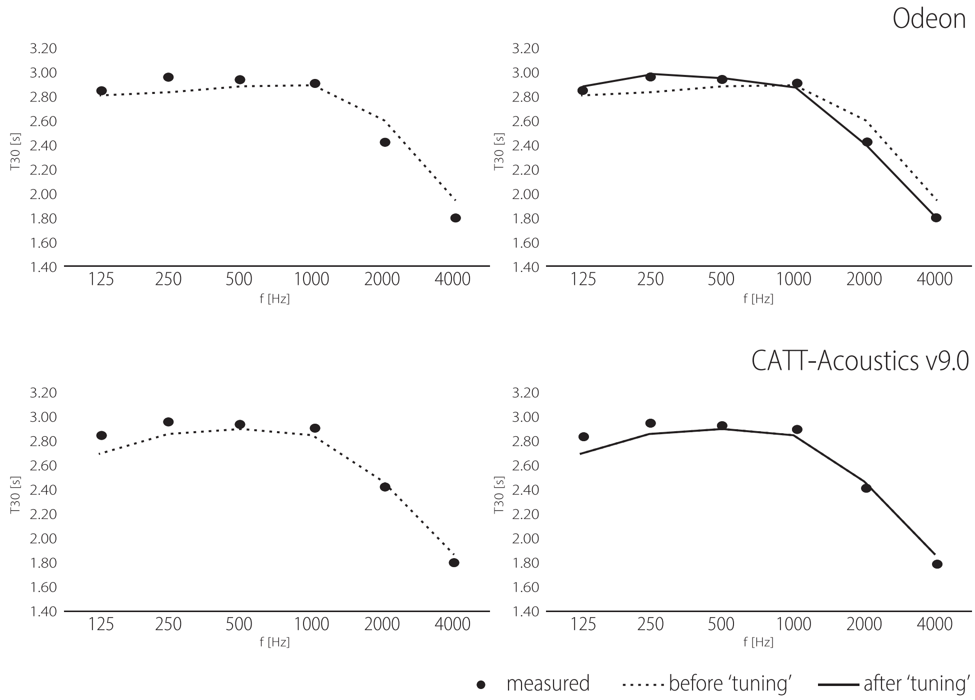

Figure 4.2: Measured and simulated average values of T30[s] in octave bands[Hz] obtained by Odeon (top) and CATT-Acoustics v9.0 (bottom) and the model with Medium level of detail of Grosse Muzikverein, Vienna, before and after the 'tuning' process.

5. Results

After the 'tuning' process, the measured and the simulated values of RA parameters T30, C80, D50, EDT, LF were compared. The results are presented comparing 'tuned' models above and the models with different levels of detailing below in average values in octave-bands are placed side by side to the values in the receiver positions at 1kHz, to highlight the differences between mean and detailed prediction.

The names of the software are kept confidential. The aim of the research is not to devalue or phrase specific software, but to evaluate the correlation between theory implementation and practical performance and to look for limitations and strengths of every one of them. Each software is presented with a number, which is kept the same throughout the presentation.

In addition to geometry input, material properties, and GA method, computer calculation settings affected the results. Ray tracking time was longer than the expected reverberation time; 3s in concert halls and 1.5s in the canteen. Simulations reproducibility tests were made to determine a sufficient number of rays.

5.1 T30

5.1.1 Grosse Muzikverein, Vienna

Reverberation Time (T30) was the parameter used in the 'tuning' process. A good correlation between the measured and the simulated values was expected as a result.

The measured T30 values move between 2.70s and 3.10s at 1kHz, with higher values at receiver positions in the stalls, closer to the source, and just noticeably lower on balconies. The lower measured values at receiver positions 11 and 30 reflect a seat-dip effect. The phenomena occurs when the sound is reflected from the rows of seats with a phase-shift of 180° causing cancellation of pressure. It cannot be modeled by GA methods, where phase properties of sound are neglected.

The room has a typical shoebox geometry. It is symmetrical and compact in volume, with shallow balconies, high ceiling and equally distributed absorption and diffusion, making the simulated energy decay over the room less dependent on exact receiver position.

The underestimation of T30 that can be seen in the results obtained by three software and the model with H level of detail is an influence of the geometry fragmentation on the simulation outcome. The high number of small surfaces causes the elimination of the geometrically invalid ISs in the first part of the simulation process. The 'lost' rays result in faster energy decay in the early part of the echogram and consequently, low simulated T30.

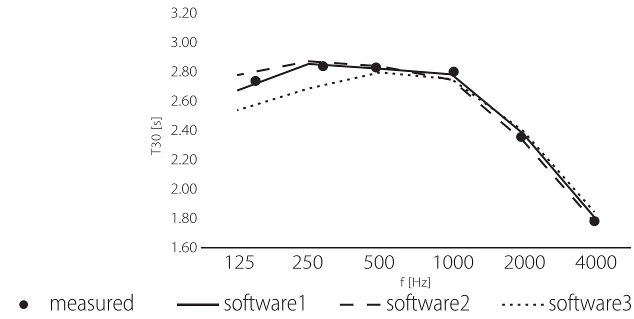

Figure 5.1: Measured and simulated average values of T30[s] in octave bands[Hz] obtained by three software and the model with Medium level of detail of Grosse Muzikverein, Vienna.

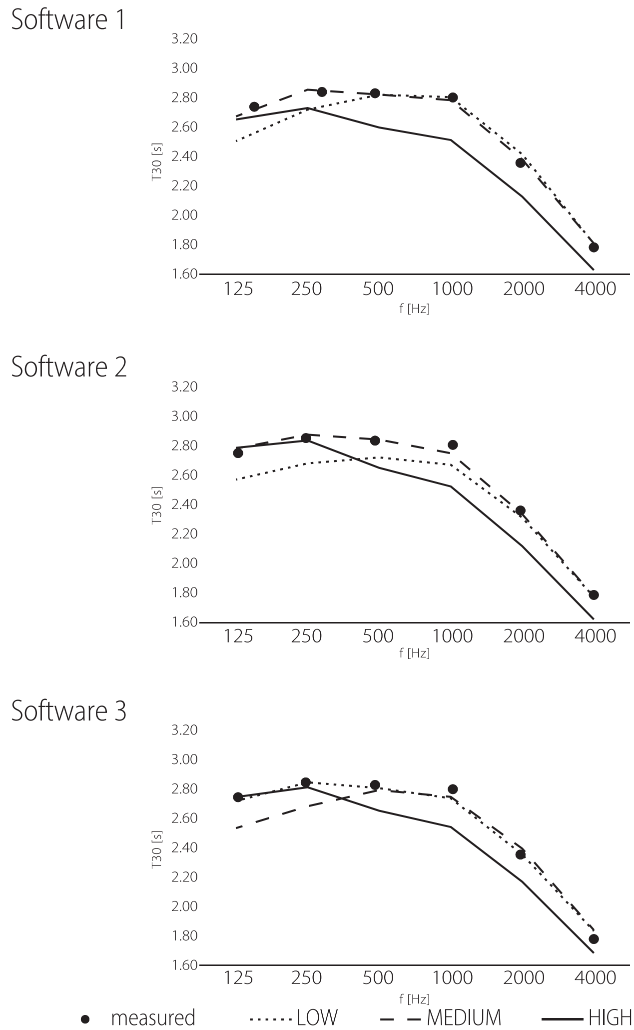

Figure 5.2: Measured and simulated average values of T30[s] in octave bands[Hz] obtained by three software and three models with Low, Medium and High level of detail of Grosse Muzikverein, Vienna.

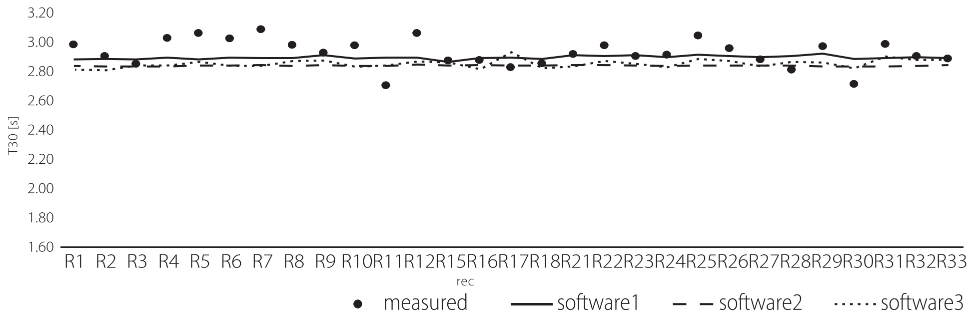

Figure 5.3: Measured and simulated average values of T30[s] over 29 receiver positions at 1kHz obtained by three software and the model with Medium level of detail of Grosse Muzikverein, Vienna.

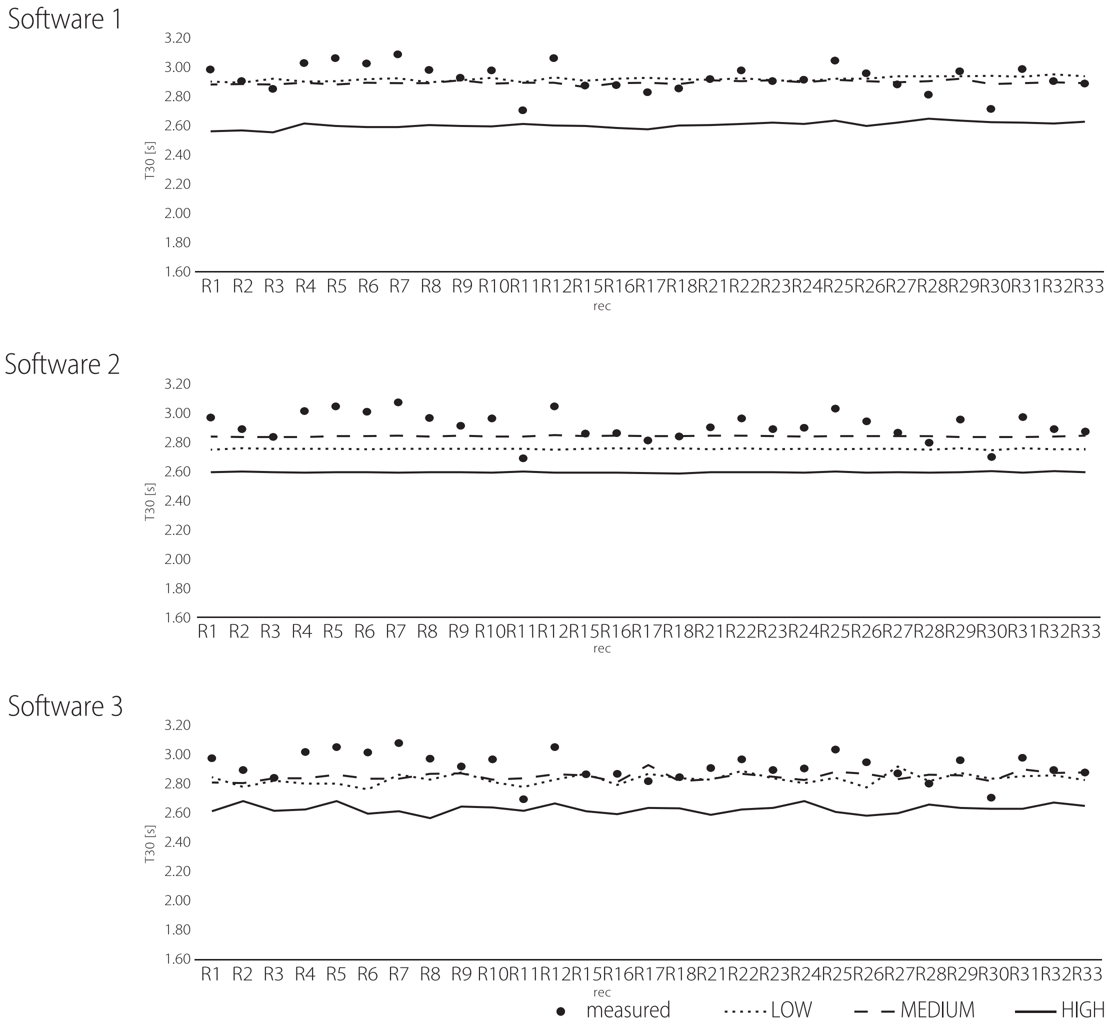

Figure 5.4: Measured and simulated average values of T30[s] over 29 receiver positions at 1kHz obtained by three software and three models with Low, Medium and High level of detail of Grosse Muzikverein, Vienna.

5.1.2 Malmö Live concert hall, Malmö

The measured mean T30 in Malmö Live concert hall is decaying over octave-bands, and it is even over the receiver positions due to the compact geometry, highly absorptive seating and even diffusion distribution.

A good correlation as a result of a precise 'tuning' process in average values did reflect in good correlation in detailed prediction by both models.

Figures B.1 and B.2 a geometry simplification in the models can be seen. The evenly distributed geometry fragmentation of diffuse elements was supplemented by scattering as presented in table 4.5. The scattering coefficient values were a result of the 'tuning' process and were applied consistently in all the software. However, the different requirements for precision can be seen in the results.

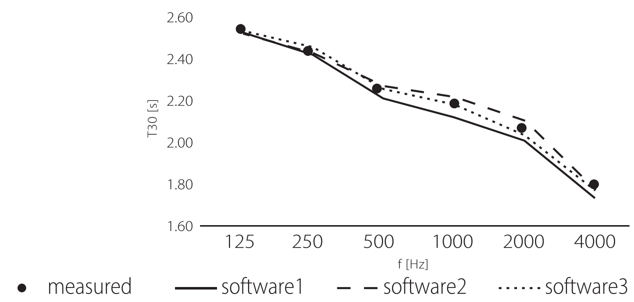

Figure 5.5: Measured and simulated average values of T30[s] in octave bands[Hz] obtained by three software and the model with Low level of detail of Malmö Live concert hall, Malmö.

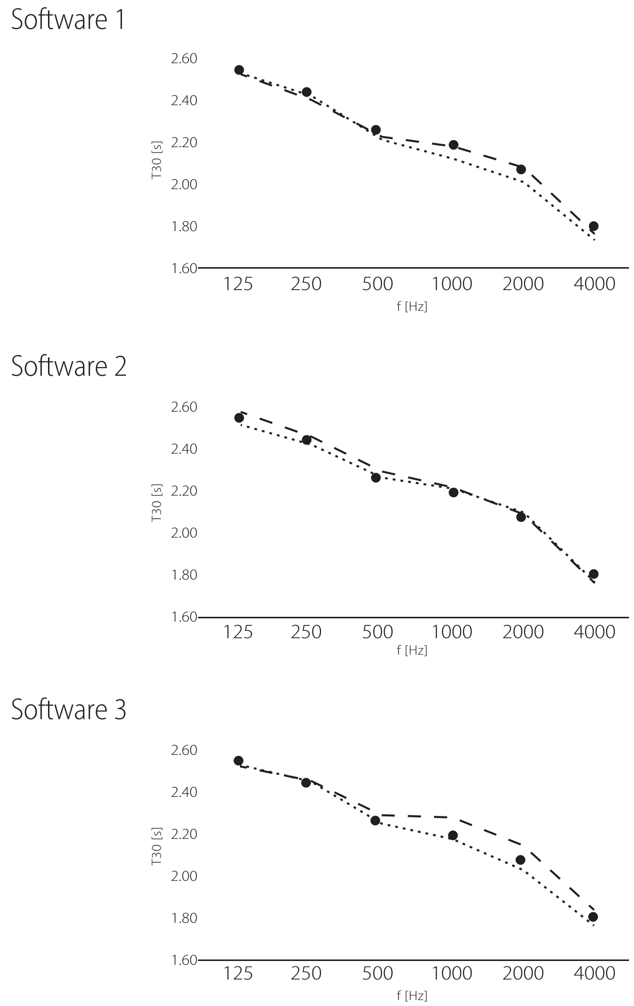

Figure 5.6: Measured and simulated average values of T30[s] in octave bands[Hz] obtained by three software and two models with Low and Medium level of detail of Malmö Live concert hall, Malmö.

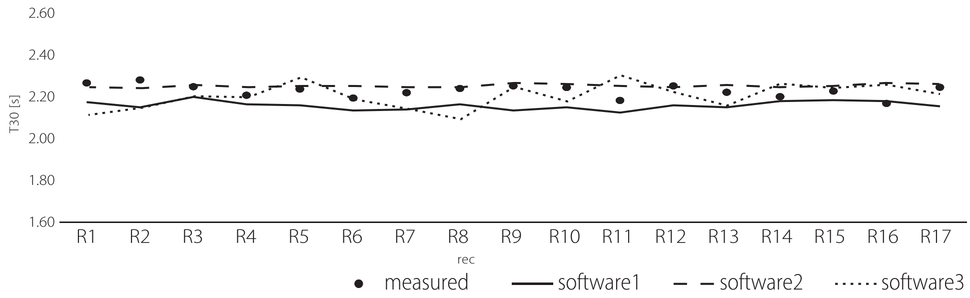

Figure 5.7: Measured and simulated average values of T30[s] over 17 receiver positions at 1kHz (right) obtained by three software and the model with Low level of detail of Malmö Live concert hall, Malmö.

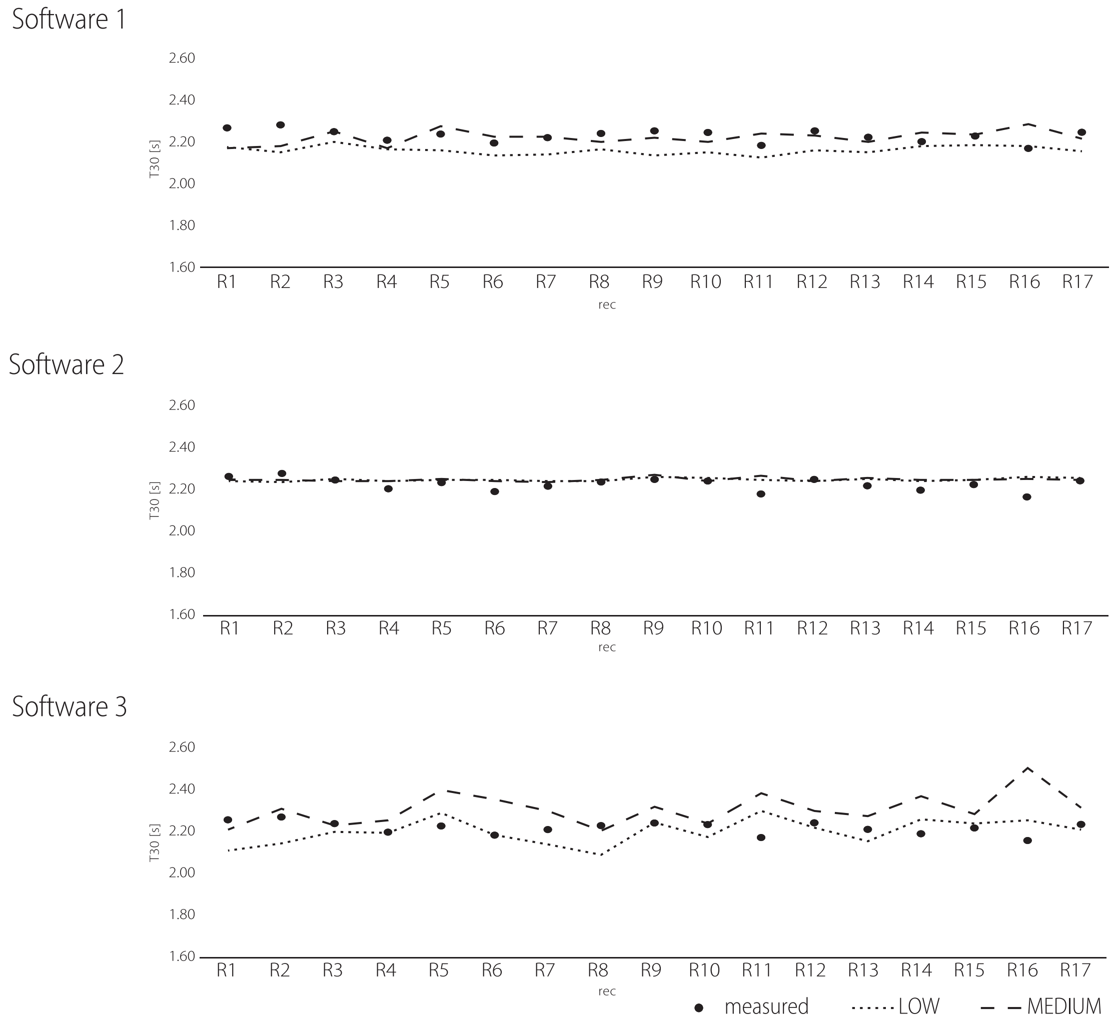

Figure 5.8: Measured and simulated average values of T30[s] over 17 receiver positions at 1kHz obtained by three software and two models with Low and Medium level of detail of Malmö Live concert hall, Malmö.

5.1.3 Norconsult AB Canteen, Göteborg

While the other two rooms of interest in the research can be described as a large room, the canteen has a smaller volume and it's Schroeder frequency is much higher, around 63Hz. It was expected, that the accuracy of the simulation results will decrease in frequency range closer to the resonant field of the room. The measured results also show an energy built-up as a consequence of a resonance in the 250Hz frequency band. Since 250Hz is not one of the eigenfrequencies of the room, it was explained as a natural resonance of the attaching hallway and ignored in the 'tuning' process.

The majority of the materials in the room are acoustically hard and smooth such as glass and plaster walls, marble floors. Absorption is placed on the ceiling and below the dining tables. It was expected that lack of diffusion and absorption would result in highlighted differences in GA method implementation.

The incomplete 'tuning' process can be seen in the results. The software packages that predetermine specular reflections required unreasonably high scattering, around 30% that does not exist in reality. However, the software manual did not suggest that the use of the scattering values below the determined percentage will result in bouncing rays and consequently, unrealistic results. In the software package with predetermined diffused reflections to predict the late part of the echogram, the scattering was set to 0%.

In all later presented simulation results of Norconsult AB Canteen, the incomplete 'tuning' has to be taken into account.

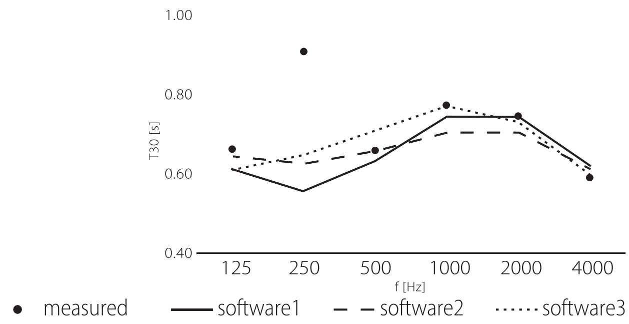

Figure 5.9: Measured and simulated average values of T30[s] in octave bands[Hz] obtained by three software and the model with High level of detail of Norconsult AB Canteen, Göteborg.

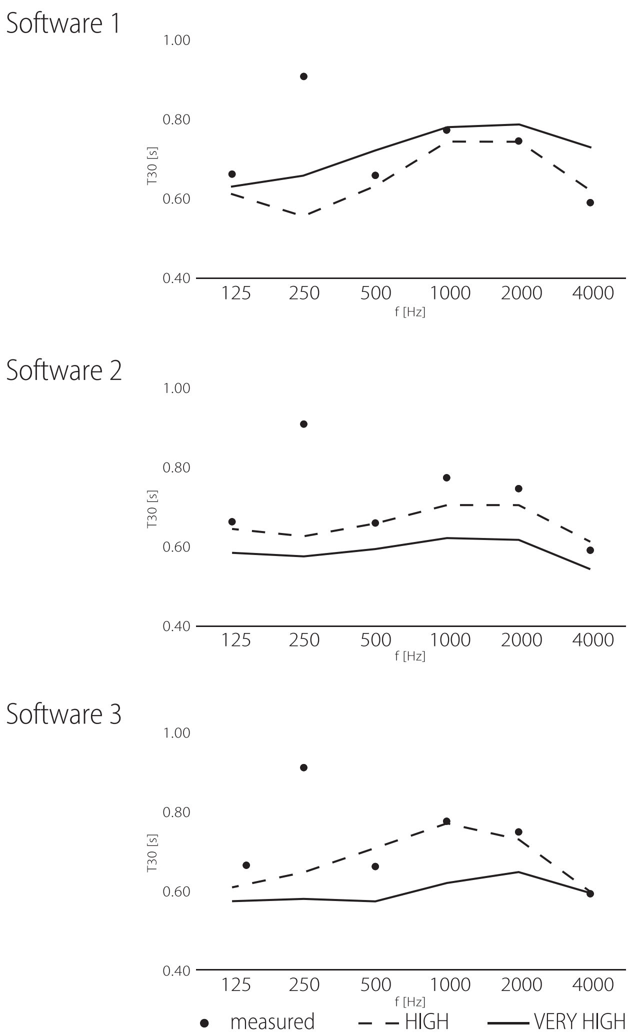

Figure 5.10: Measured and simulated average values of T30[s] in octave bands[Hz] obtained by three software and two models with High and Very High level of detail of Norconsult AB Canteen, Göteborg.

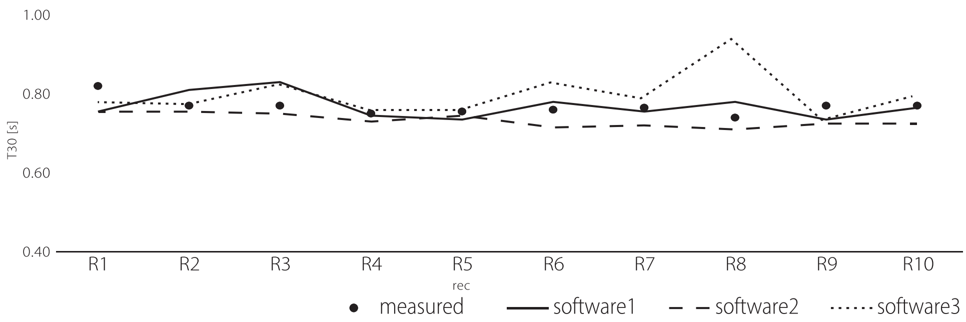

Figure 5.11: Measured and simulated average values of T30[s] over 10 receiver positions at 1kHz obtained by three software and the model with High level of detail of Norconsult AB Canteen, Göteborg.

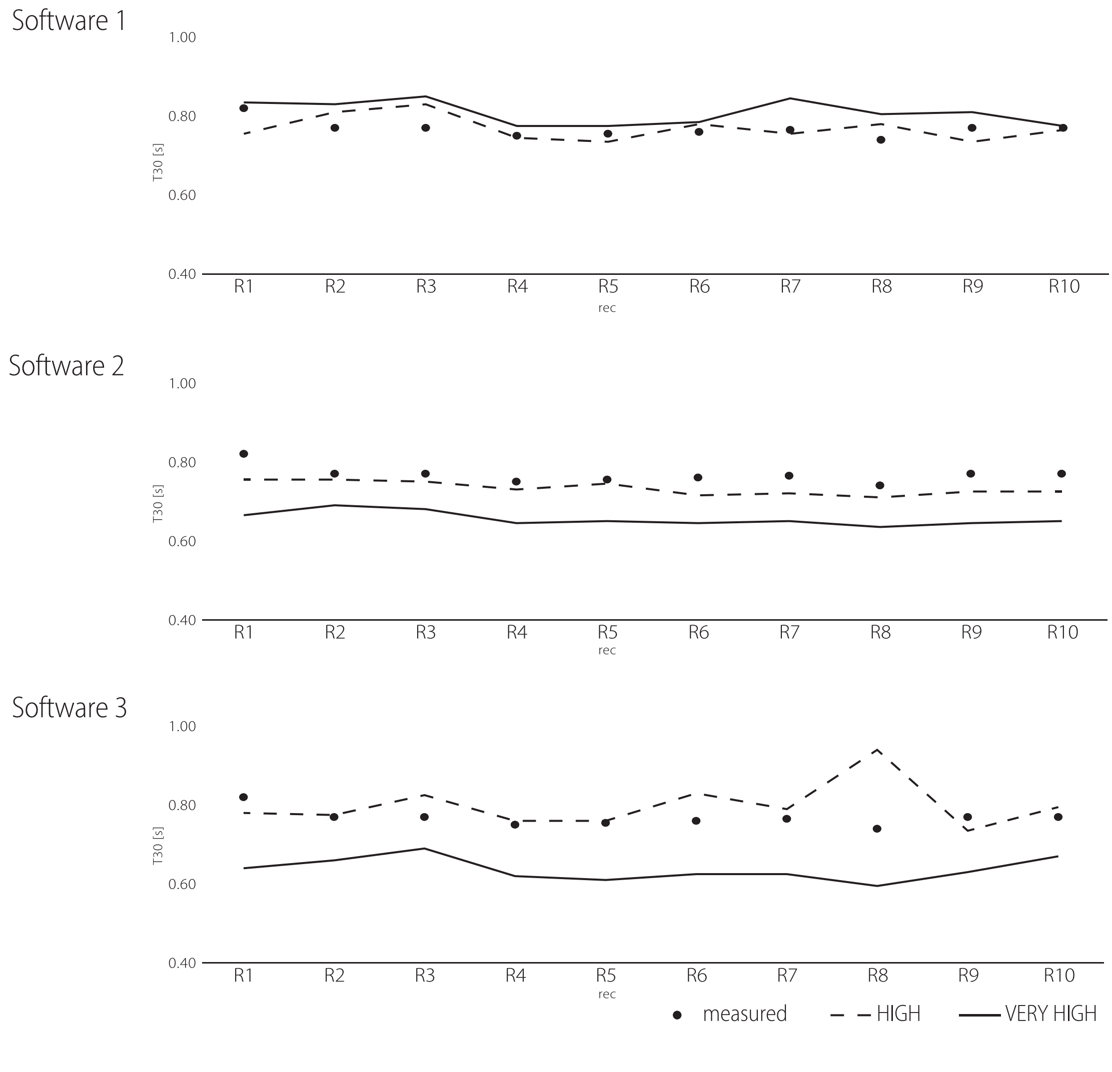

Figure 5.12: Measured and simulated average values of T30[s] over 10 receiver positions at 1kHz obtained by three software and two models with High and Very High level of detail of Norconsult AB Canteen, Göteborg.

5.2 C80

5.2.1 Grosse Muzikverein, Vienna

Clarity (C80) is a parameter describing a balance of early and late reflections. It is calculated as a ratio of energy arriving in the first 80ms and energy after 80ms. Since it highlights the precision in the first part of the echogram, a high dependence on the receiver position was expected.

Two important factors are affecting the simulated C80. The software implementation of direct sound detection when it is cut-off by geometry explained in section 3.1 and audience area modeling. The source is positioned above the audience surface that provides a strong first reflection, which is in simulation shifted to the early part. In reality, this reflection from the floor arrives later. It results in higher simulated C80 values.

A good sound conditions in a concert hall are described with the values of C80 in the range -4dB to 4dB. It can be seen that the average measured values of C80 in Grosse Muzikverein are in the range from -4dB to 0dB.

High dependency of C80 on receiver position can be seen in measured and simulated values.

The measured C80 values are lower in positions from 7 to 12. These are the positions in the back part of the stalls, affected by higher absorption of the audience due to the narrow angle of incidence of the direct sound. The phenomena can only be simulated by the software implementing angle of incidence dependent absorption.

More understanding in the detailed simulation is offered by observation of the values at the first two positions on the loges; positions 15 and 16. Non-existing higher C80 values are predicted by all the software. The strong direct sound energy adds up with strong first reflections from the audience area, the side wall, and the upper balcony ceiling. The effect can be avoided with different audience area modeling and precise evaluation of diffusion close to the sound source.

The positions 17, 21 and 23 are placed on the balcony loge with balcony front barrier. The measured and simulated parameter values are lower due to the unclear direct sound path. The results obtained by different software are coherent, regardless the direct sound detection implementation.

The general movement of the simulated results over positions gives an impression of a simple shift of curves higher with the level of detail in the model, showing that the elimination of the early rays in the first part of the simulation process has an impact on the simulated values of C80 as well as T30.

It can be concluded, that the differences in implementation of the direct sound detection do not effect the simulated result. For a better understanding of audience area modeling, detailed research is presented in chapter 6.

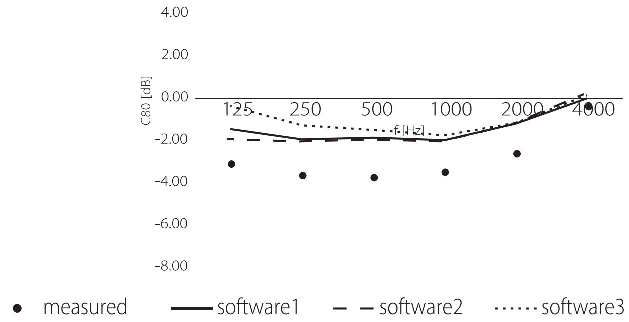

Figure 5.13: Measured and simulated average values of C80[dB] in octave bands[Hz] obtained by three software and the model with Medium level of detail of Grosse Muzikverein, Vienna.

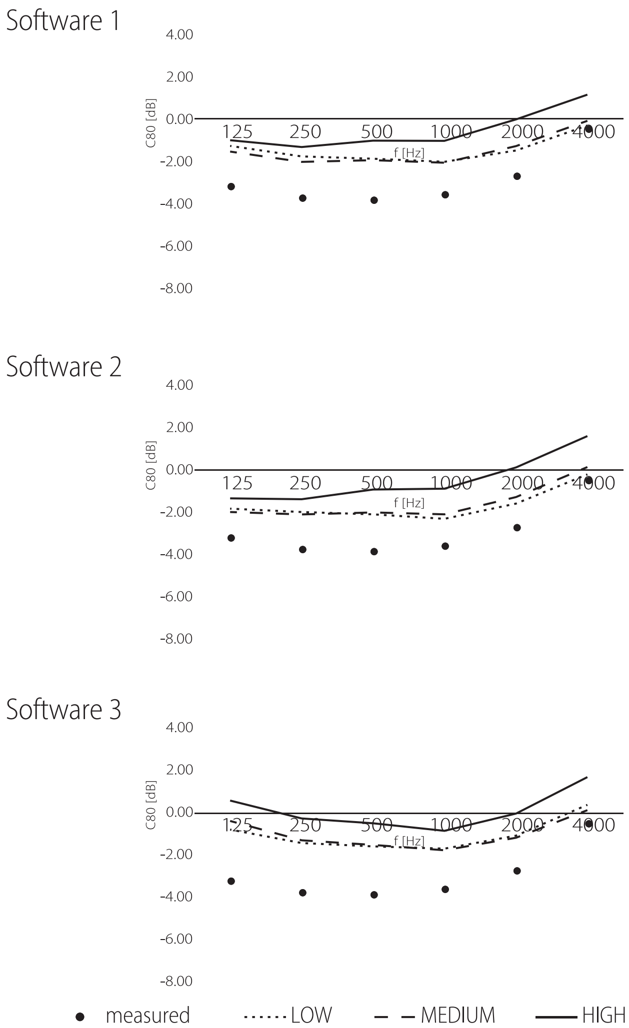

Figure 5.14: Measured and simulated average values of C80[dB] in octave bands[Hz] obtained by three software and three models with Low, Medium and High level of detail of Grosse Muzikverein, Vienna.

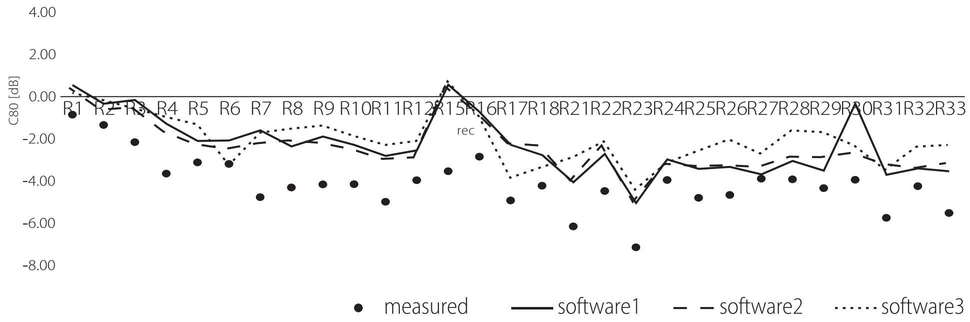

Figure 5.15: Measured and simulated average values of C80[dB] over 29 receiver positions at 1kHz obtained by three software and the model with Medium level of detail of Grosse Muzikverein, Vienna.

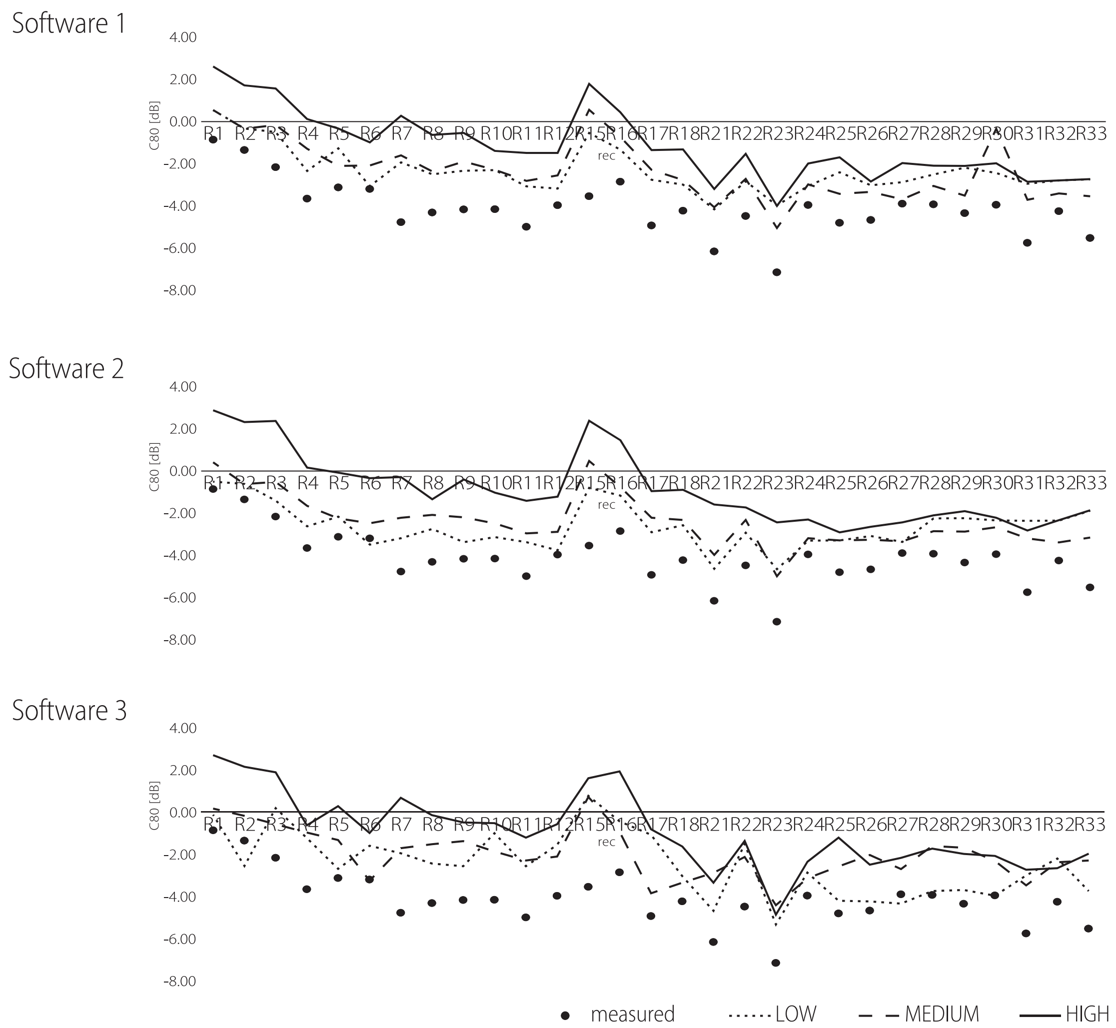

Figure 5.16: Measured and simulated average values of C80[dB] over 29 receiver positions at 1kHz obtained by three software and three models with Low, Medium and High level of detail of Grosse Muzikverein, Vienna.

5.2.2 Malmö Live concert hall, Malmö

The average simulated C80 obtained by the three software and two models with different levels of detail show overestimation of the parameter values. The deviations in results obtained by different software are even higher in lower frequency bands.

The detailed measured and simulated C80 show the high dependency on the specific position of the receiver in the room; values are higher close to the stage, lowering with the increase in the distance. Over-stage reflector is a relevant geometrical element that shortens the time delay of the first ceiling reflection in all positions, balancing the measured C80 values.

Analysis of the results obtained by two models highlights the precision on diffusion evaluation and implementation in different software algorithms.

The receivers 5, 10, 13 and 17 are positioned close to the diffusive wall in different levels, in the stalls, first, second and third side balcony. The measured values at the positions are lower as a consequence of three components; direct sound cut-off, source-receiver distance and highly diffusive properties of the wall. The main dips in simulated and measured results are overlapping, suggesting the three components can be accurately simulated with GA methods. These are also the positions where the differences between different software packages are most apparent; predetermined diffused reflections for predicting the late part of the echogram result in higher coherence in predictions obtained by two different models.

The receivers 9 and 14 are also placed on the side balconies, but the measured, as well as the simulated values, are less extreme due to the shorter source-receiver distance.

Less directly influenced by the diffusive side walls and ceiling are receivers 7, 8, 11, 12 and 15, 16 on various levels on the balconies. The C80 values in these positions are higher in simulated and measured results as a consequence of the reflection from the over-hanging balcony. These are also the positions where different software predict similar results.

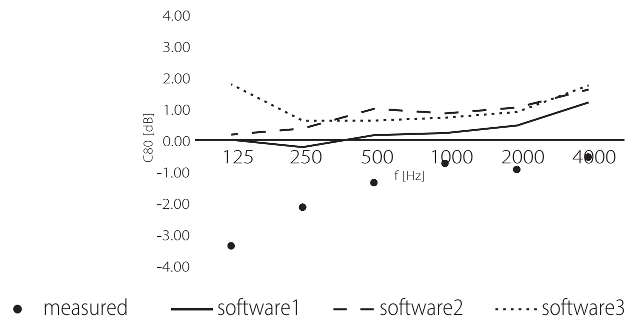

Figure 5.17: Measured and simulated average values of C80[dB] in octave bands[Hz] obtained by three software and the model with Low level of detail of Malmö Live concert hall, Malmö.

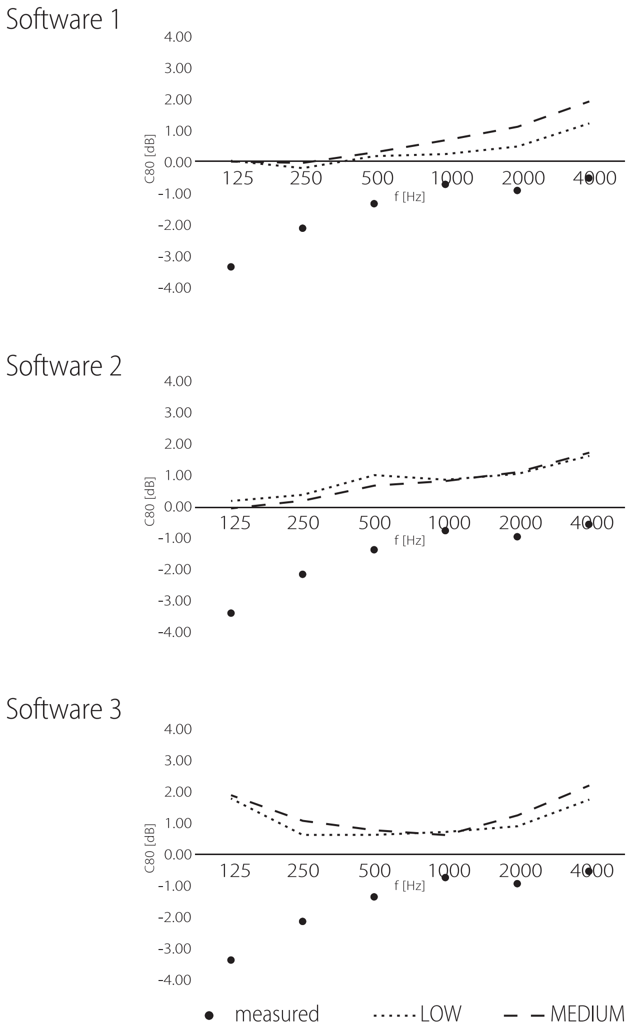

Figure 5.18: Measured and simulated average values of C80[dB] in octave bands[Hz] obtained by three software and two models with Low and Medium level of detail of Malmö Live concert hall, Malmö.

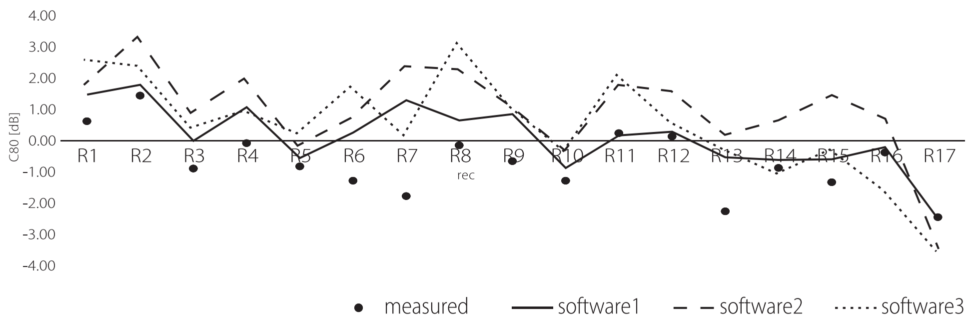

Figure 5.19: Measured and simulated average values of C80[dB] over 17 receiver positions at 1kHz obtained by three software and the model with Low level of detail of Malmö Live concert hall, Malmö.

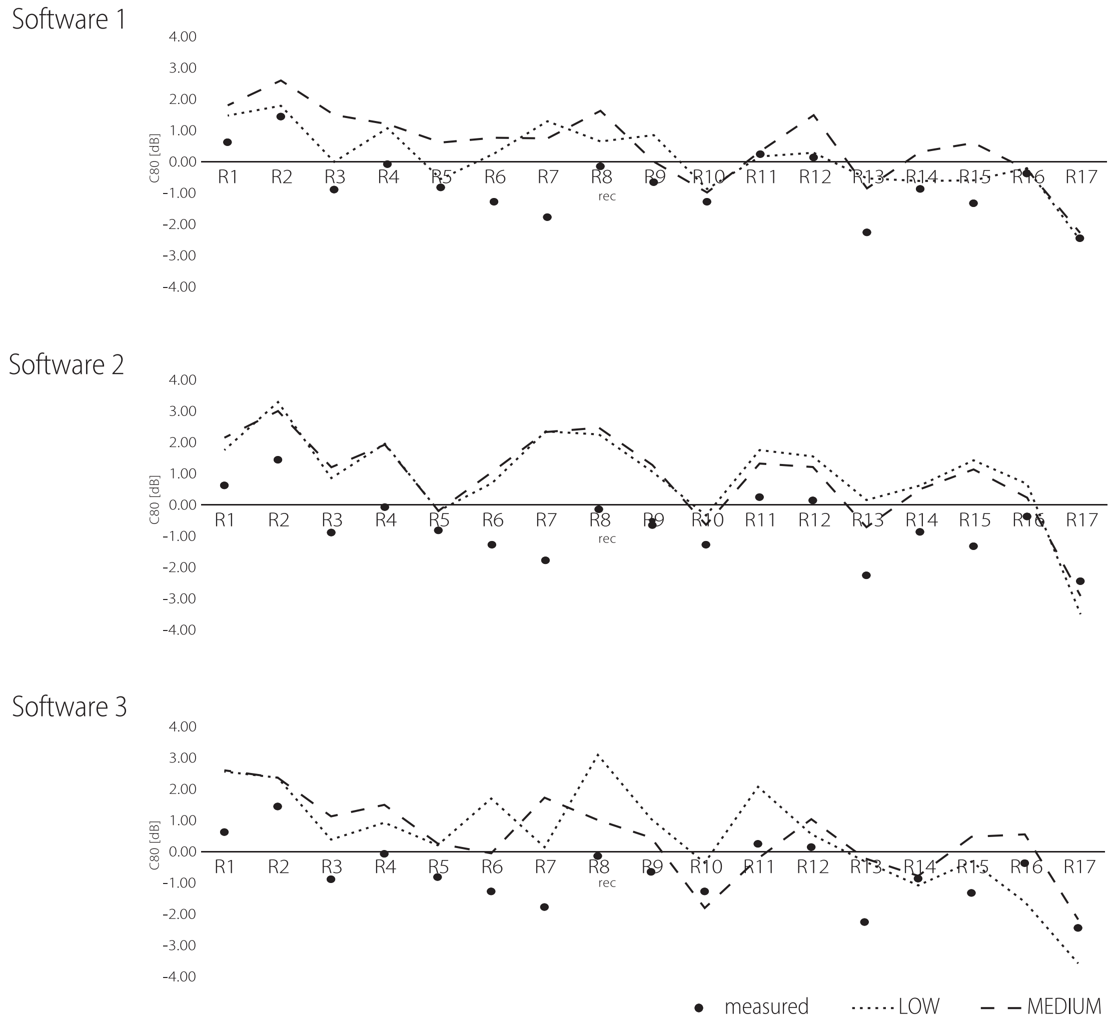

Figure 5.20: Measured and simulated average values of C80[dB] over 17 receiver positions at 1kHz obtained by three software and two models with Low and Medium level of detail of Malmö Live concert hall, Malmö.

5.3 D50

5.3.1 Norconsult AB Canteen, Göteborg

Definition (D50) is calculated as a ratio of the energy in the first 50ms and total energy in the room. It has strong similarities to C80, but % scaling is used.

The parameter is used to describe the sound quality in rooms for speech. Even though Norconsult AB Canteen cannot be put in the exact category, the shortened early part was expected to give more clear insight in the room response.

The low correlation of the measured and simulated results is based on incomplete 'tuning' process with ignored resonance in frequency band 250Hz.

In contrast to equally distributed measured values over the receiver positions, the simulations predict higher C80 at the receivers 4, 5 and 8. These are the closest receivers to the source position 2. Strong direct sound and a high number of rays that are lost in adjusted hallway result in higher parameter values. Low absorption and scattering properties of the glass and plastered walls and consequently strong flutter-echoes reflect in lower C80 at other positions.

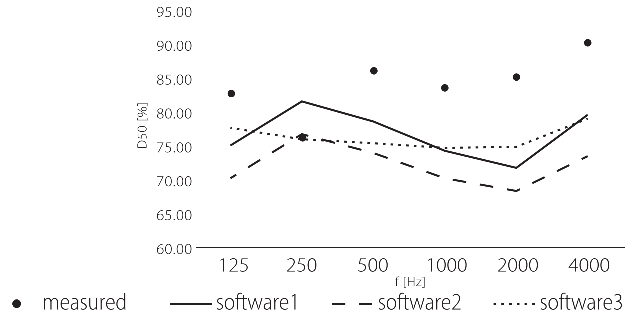

Figure 5.21: Measured and simulated average values of D50[%] in octave bands[Hz] obtained by three software and the model with High level of detail of Norconsult AB Canteen, Göteborg.

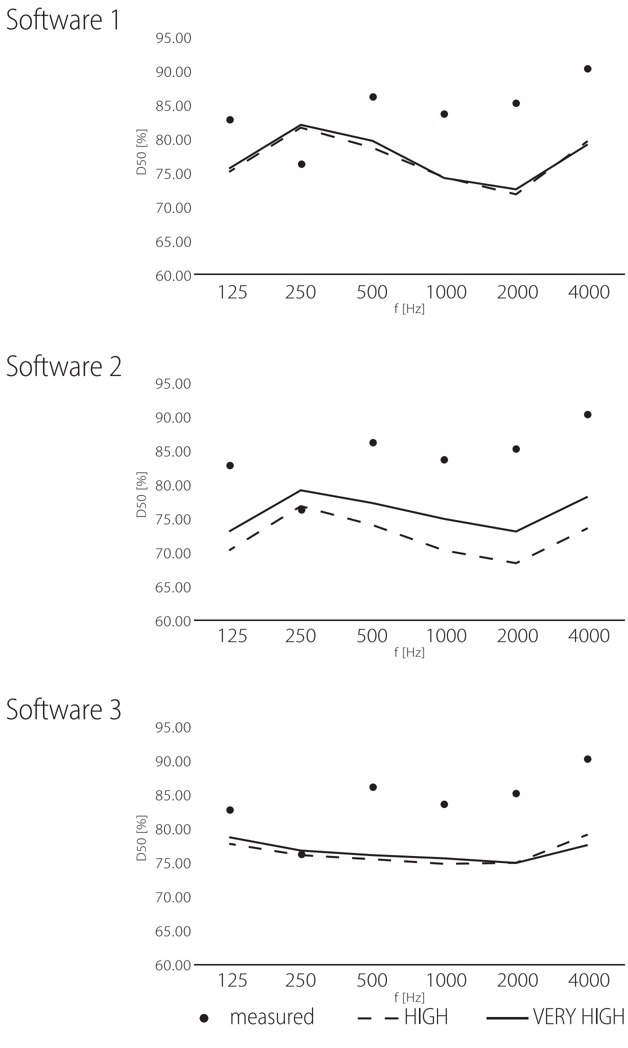

Figure 5.22: Measured and simulated average values of D50[%] in octave bands[Hz] obtained by three software and two models with High and Very High level of detail of Norconsult AB Canteen, Göteborg.

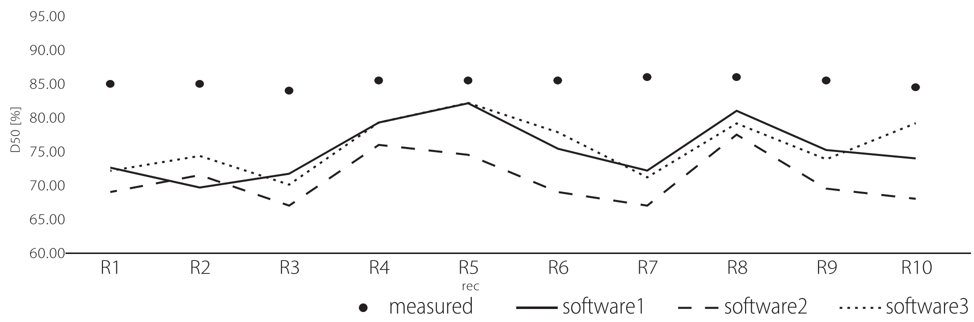

Figure 5.23: Measured and simulated average values of D50[%] over 10 receiver positions at 1kHz obtained by three software and the model with High level of detail of Norconsult AB Canteen, Göteborg.

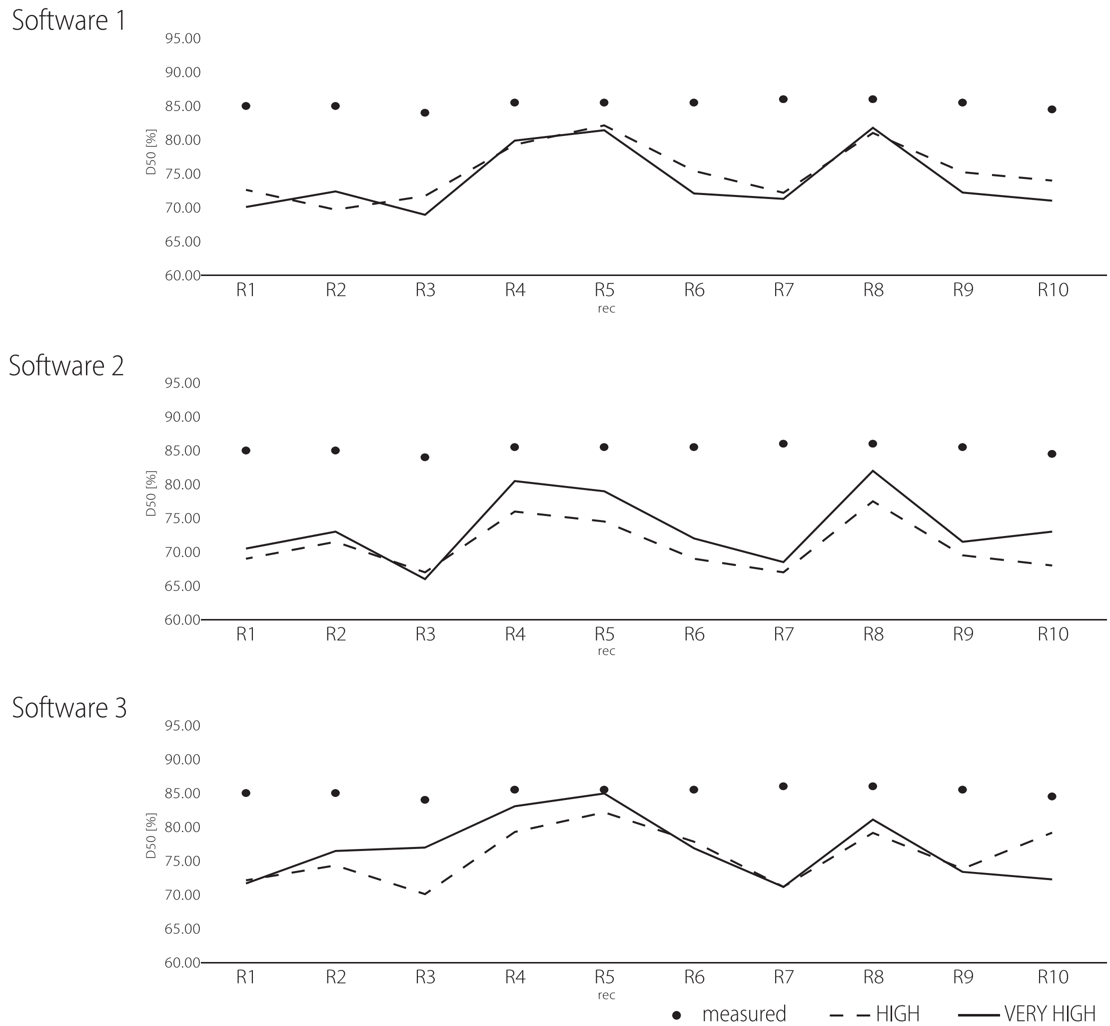

Figure 5.24: Measured and simulated average values of D50[%] over 10 receiver positions at 1kHz obtained by three software and two models with High and Very High level of detail of Norconsult AB Canteen, Göteborg.

5.4 EDT

5.4.1 Grosse Muzikverein, Vienna

Early Decay Time (EDT) is a parameter defined as a time needed for the first 10dB decay in a room, multiplied by 6 enabling easier comparison with T30. Since T30 considers the decay range from -5dB to -35dB and EDT from 0dB to -10dB, a stronger relationship with direct sound was expected.

The same basic methods to predict the the early part of the echogram, ISM and RT or CT as an extension of RT, were expected to reflect in small differences in simulation results obtained by the three software, less influenced by the method than by the geometry.

As a consequence of the 'tuning' process and above explained relation between T30 and EDT, the simulated average values are coherent with the measured. The results obtained by the model with high level of detail show overall underestimation of the parameter values due to high number of lost rays in the first part of the simulation process.

Over the receiver positions, the measured EDT values are fluctuating between 2.7s and 3.1s in front stalls, becoming more constant with increased distance from the source.

By all the software, the receiver positions on the loges, 15 and 16 are determined as extreme positions; These are the positions where strong direct sound energy adds up with strong first reflections from the audience area, the side wall, and the upper balcony ceiling.

The direct sound termination in the positions 17, 21 and 23 reflects in higher EDT predicted by all three of the software. Strong reflections from the enveloping surfaces and strong direct sound due to short distance between source and receiver reflect in lower predicted in EDT values.

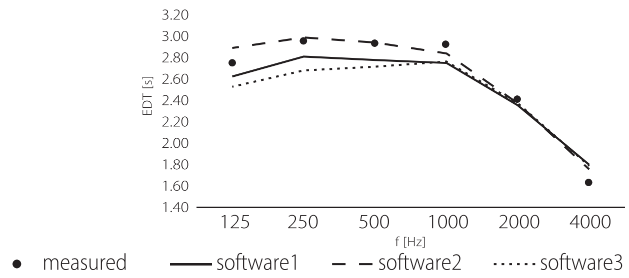

Figure 5.25: Measured and simulated average values of EDT[s] in octave bands[Hz] obtained by three software and the model with Medium level of detail of Grosse Muzikverein, Vienna.

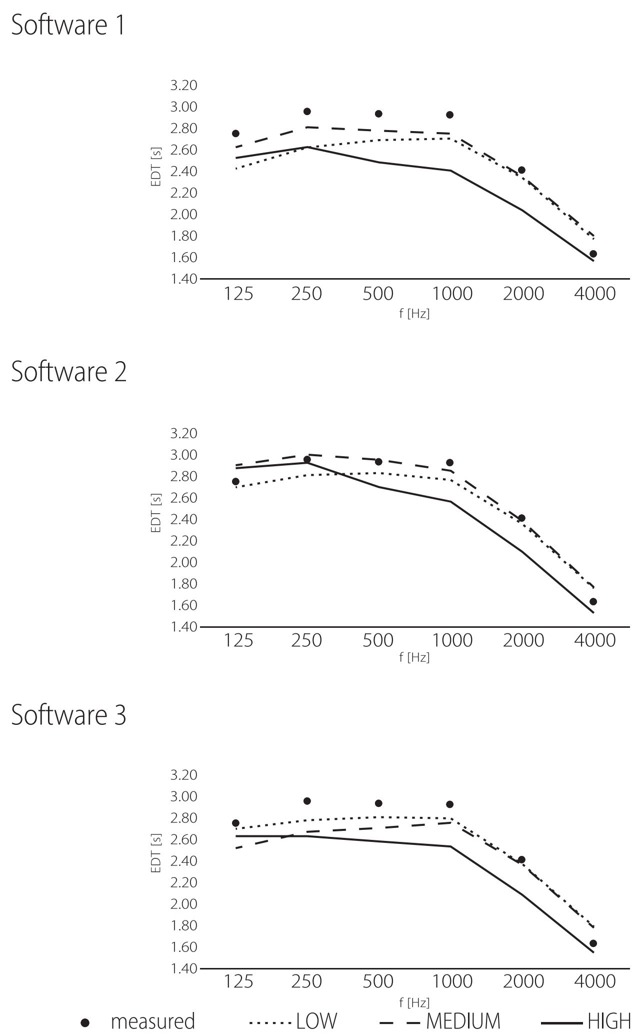

Figure 5.26: Measured and simulated average values of EDT[s] in octave bands[Hz] obtained by three software and three models with differing level of detail of Grosse Muzikverein, Vienna.

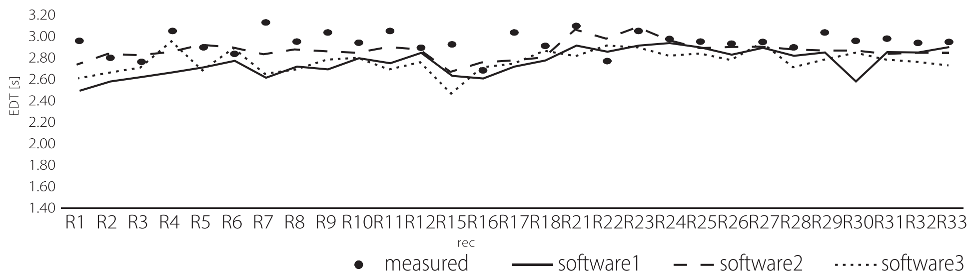

Figure 5.27: Measured and simulated average values of EDT[s] over 29 receiver positions at 1kHz obtained by three software and the model with Medium level of detail of Grosse Muzikverein, Vienna.

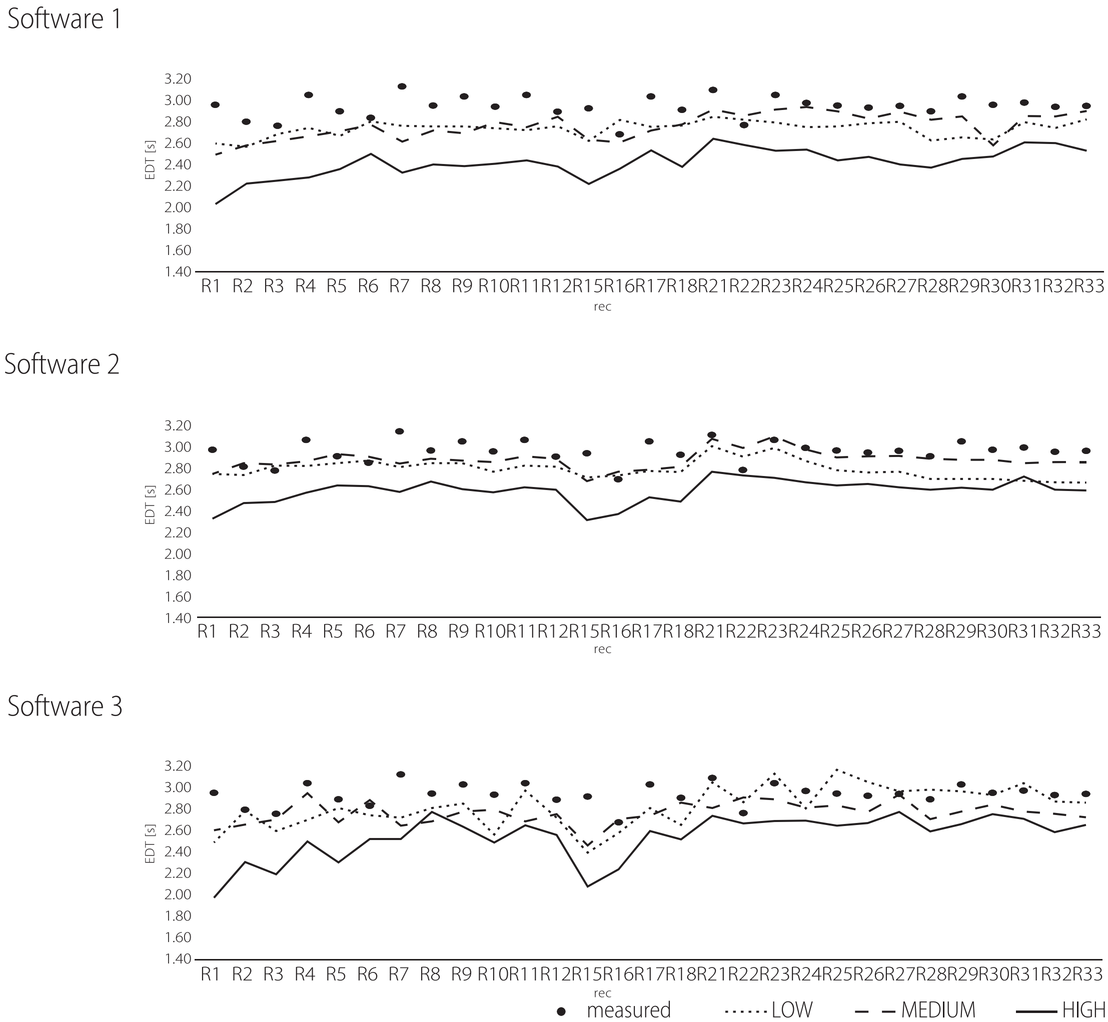

Figure 5.28: Measured and simulated average values of EDT[s] over 29 receiver positions at 1kHz obtained by three software and three models with differing level of detail of Grosse Muzikverein, Vienna.

5.4.2 Malmö Live concert hall, Malmö

The dependency of EDT on position of the receiver in the room can be seen in 5.32.

The measurement results show higher EDT values in receiver positions 9, 10, 13, 14 and 17 reflected in simulation results by all the software in the model with Medium level of detail. The results at the same receiver positions obtained by the model with Low level vary significantly comparing the results obtained by different software, reflecting the impact of substitution of the complex geometry with higher surface scattering; The first reflection from the scattering wall is reflected in a random angle), resulting in low EDT values. A better coherence can be seen in the results obtained by the software with predetermined diffuse reflections for predicting the late part of the echogram, scattering implementation dependent on surface size and source-receiver distance.

In the positions 7, 8, 11, 12 and 15, 16, the over-hanging balcony shadow is reflected in low simulated EDT values.

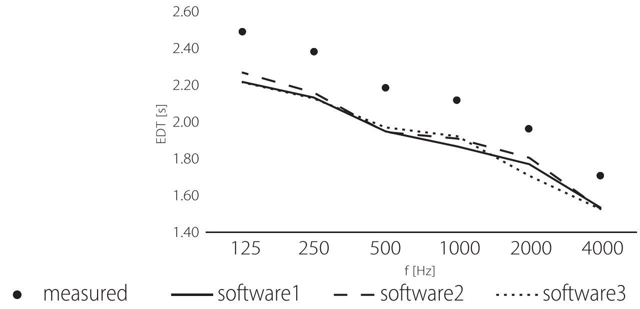

Figure 5.29: Measured and simulated average values of EDT[s] in octave bands[Hz] obtained by three software and the model with Low level of detail of Malmö Live concert hall, Malmö.

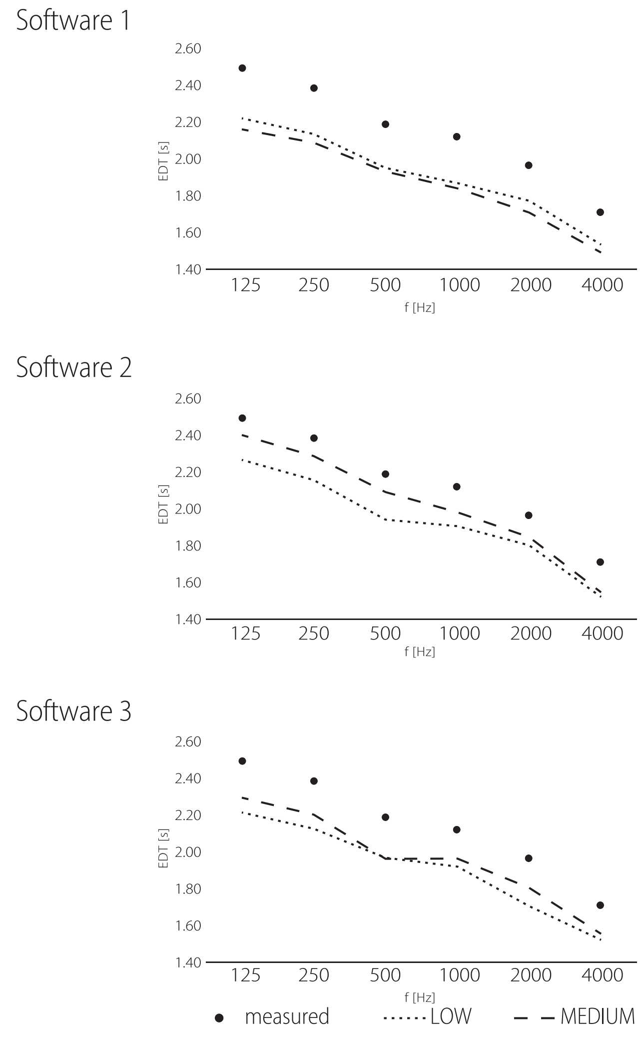

Figure 5.30: Measured and simulated average values of EDT[s] in octave bands[Hz] obtained by three software and two models with Low and Medium level of detail in Malmö Live concert hall, Malmö.

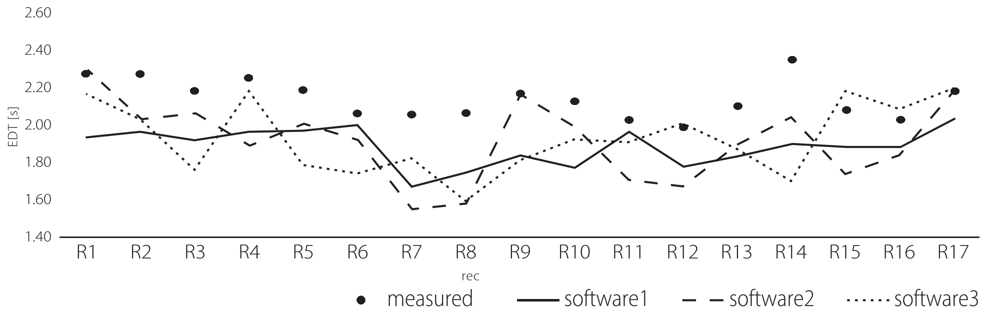

Figure 5.31: Measured and simulated average values of EDT[s] over 17 receiver positions at 1kHz obtained by three software and the model with Low level of detail of Malmö Live concert hall, Malmö.

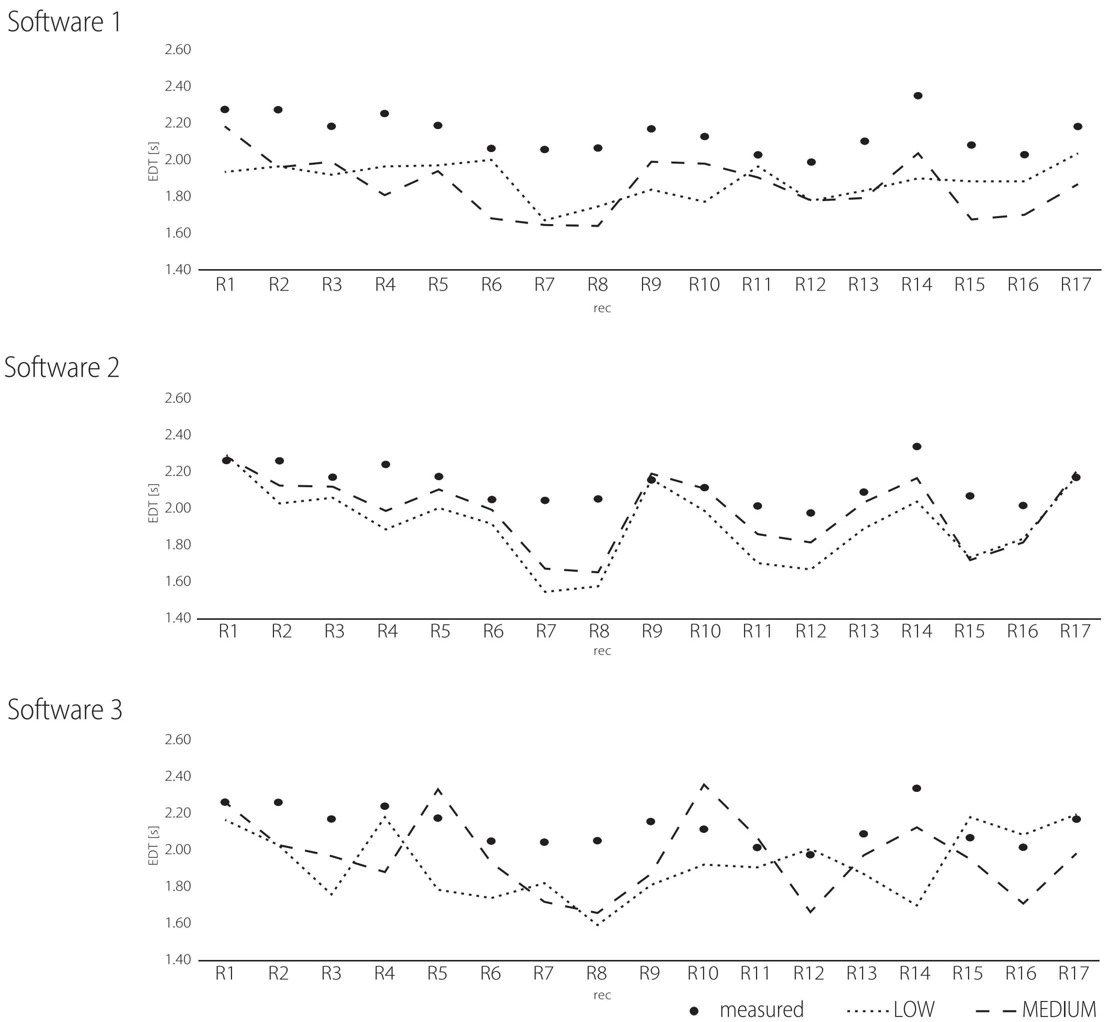

Figure 5.32: Measured and simulated average values of EDT[s] and over 17 receiver positions at 1kHz obtained by three software and two models with Low and Medium level of detail in Malmö Live concert hall, Malmö.

5.4.3 Norconsult AB Canteen, Göteborg

The small size and the rectangular geometry of the room and small distances between the source and the receivers result in fast early energy decay over all the receiver positions resulting in steady measured parameter values.

The errors, such as flutter echoes between parallel and acoustically hard walls due to lack of absorption and diffusion properties of the room surfaces, occur later in the simulation process, a good coherence of the measured and the simulated values can be seen in figures 5.34 and 5.36. The precision of the 'tuning' process has to be taken into account.

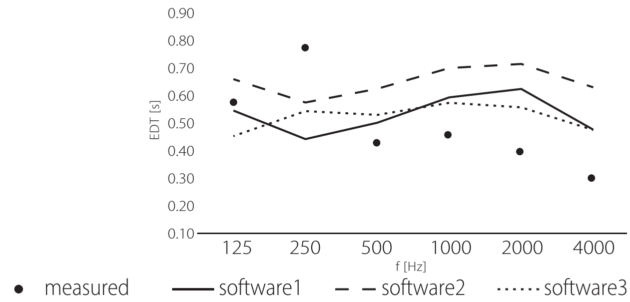

Figure 5.33: Measured and simulated average values of EDT[s] in octave bands[Hz] obtained by three software and the model with High level of detail of Norconsult AB Canteen, Göteborg.

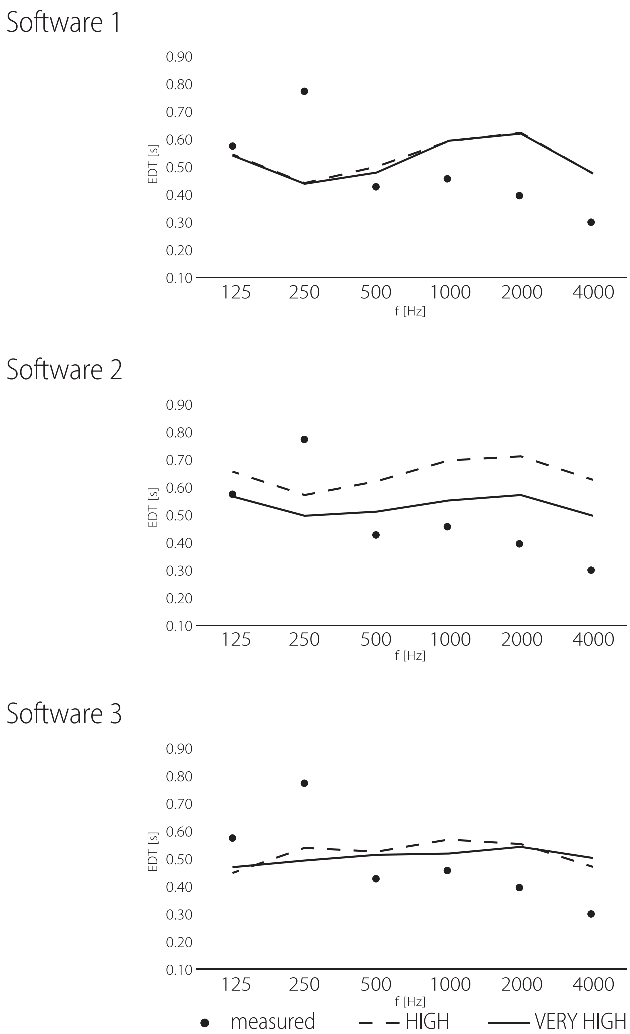

Figure 5.34: Measured and simulated average values of EDT[s] in octave bands[Hz] obtained by three software and two models with High and Very High level of detail in Norconsult AB Canteen, Göteborg.

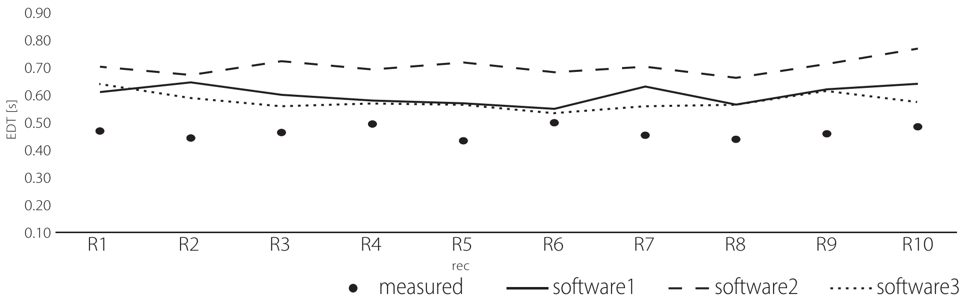

Figure 5.35: Measured and simulated average values of EDT[s] over 10 receiver positions at 1 kHz obtained by three software and the model with High level of detail of Norconsult AB Canteen, Göteborg.

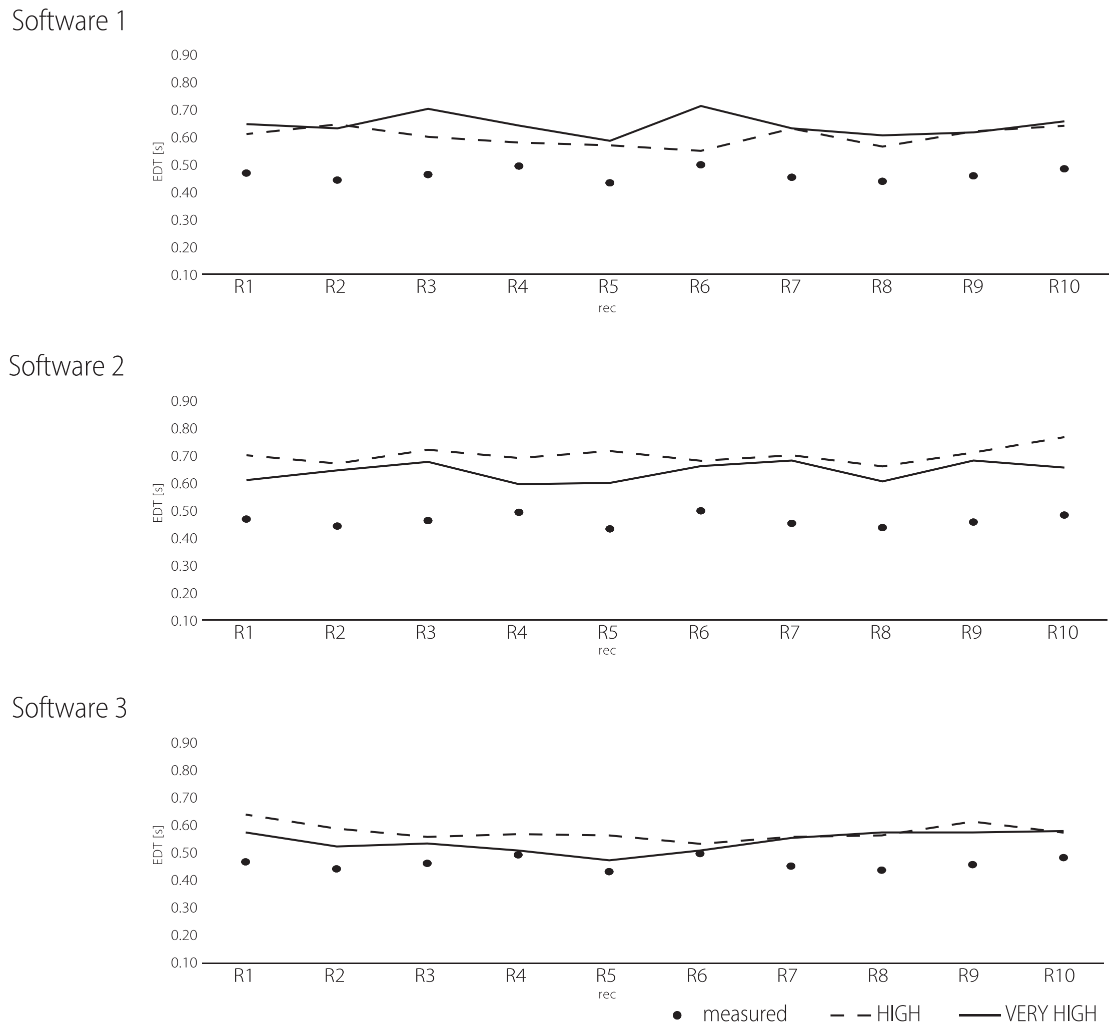

Figure 5.36: Measured and simulated average values of EDT[s] over 10 receiver positions at 1kHz obtained by three software and two models with High and Very High level of detail in Norconsult AB Canteen, Göteborg.

5.5 LF

5.5.1 Malmö Live concert hall, Malmö

Lateral energy Fraction (LF) is a parameter defined as a ratio of the laterally reflected sound energy in a room over sound energy arriving from all directions including the direct sound energy. It takes into account sound direction and timing.

Because of the complex parameter calculation and scattering application by randomization of the diffused rays, the lower accuracy of the simulation results was expected.

In figure 5.37 can be seen that the measured average values for LF are around 20% and slowly decaying at higher frequency bands, achieving 15% at 4kHz.

The parameter is highly dependent on the position of the receiver in the room, more so, when it is placed out of the central line and close to the diffusive wall.

The receiver positions 9 and 14 are defined as the extreme positions in the simulation results obtained by all the software and two different models. The positions are placed on the first and second side balcony, with a short distance from the sound source. The receiver position 9 is a typical position with high LF values due to the closeness to the wall. The substitution of geometrical fragmentation with higher scattering coefficient intensifies the effect due to he randomized reflection angles. The angle of incidence of the direct sound and reflections from the upper balcony floor reflect in lower parameter values in position 14. In reality, the behavior is weakened by the diffusive side wall and can not be seen in the measured parameter values.

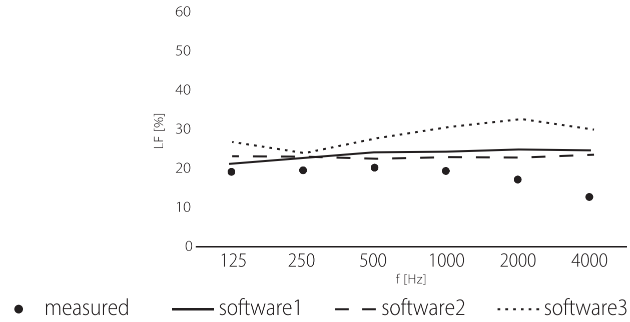

Figure 5.37: Measured and simulated average values of LF[%] in octave bands[Hz] obtained by three software and the model with Low level of detail of Malmö Live concert hall.

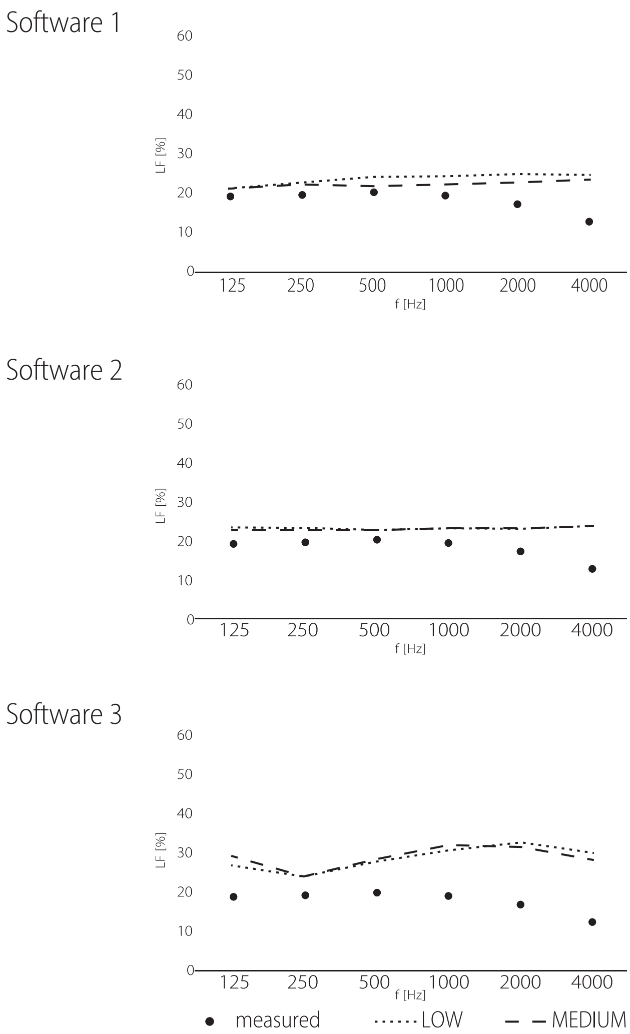

Figure 5.38: Measured and simulated average values of LF[%] in octave bands[Hz] obtained by three software and two models with Low and Medium level of detail in Malmö Live concert hall, Malmö.

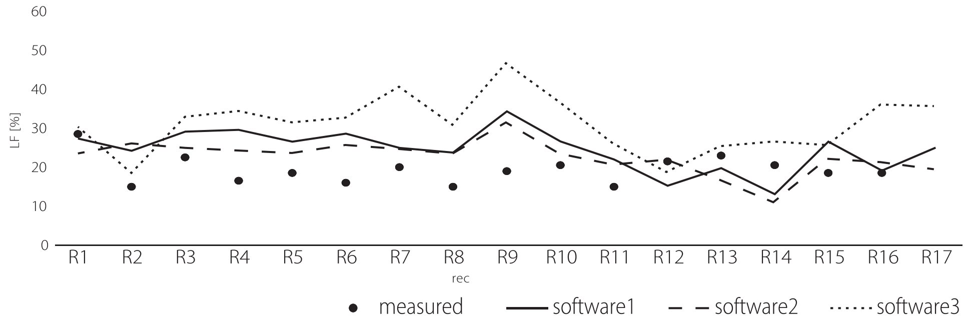

Figure 5.39: Measured and simulated average values of LF[%] over 10 receiver positions at 1 kHz obtained by three software and the model with Low level of detail of Malmö Live concert hall.

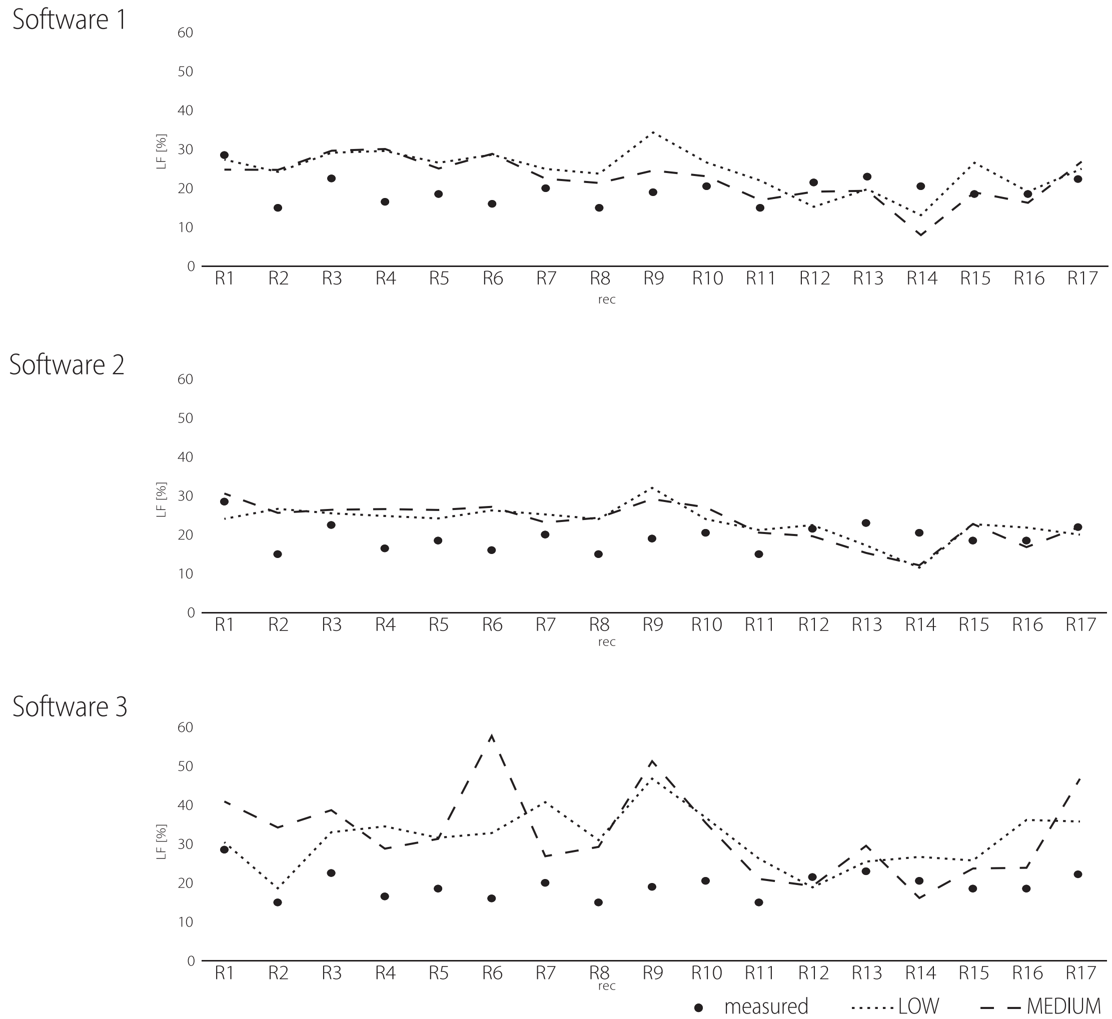

Figure 5.40: Measured and simulated average values of LF[%] over 17 receiver positions at 1kHz obtained by three software and two models with Low and Medium level of detail in Malmö Live concert hall, Malmö.

6. Audience area modeling

In every performance space or auditorium, a large area is dedicated to the audience. Occupied or unoccupied with fixed or removable seating, the area is geometrically complex and constantly changing. Acoustically, it strongly affects the sound environment. The question arising in the context of the RA computer simulations is: how and to what extent should the complex shape of a human body or a chair be simplified in a computer model?

The most commonly used approach in general practice is to model the audience using a box or a plane at shoulders hight of a seated person, about 0.9m above the floor surface. The receivers placed 0.3m above the box or the plane representing the position of a human ear.

In his research [18] A. B. Nagy has compared two most commonly used approaches; audience area modeled as a box or as a plane. The conclusion of the research was clear; when the box approach is used, the absorption of the audience tends to be underestimated and the plane approach results in trapped rays between the floor and floating plane and consequently in faster energy decay. The differences in predicted results using different approaches were proven to be small; the average T30 deviation was less than 2.5% in mid-frequency range.

In the same research [18] A.B. Nagy addresses the problem of the strong first reflection from the audience box or the plane detected by the receiver placed close to the surface. In reality, the sound reflected from the floor arrives with much longer time delay. He proposes a way to overcome the problem; to model the audience plane slightly above the floor surface to the needed absorption and diffusion, without the hard reflections. The deviation in predicted results is comparable to the deviation in different modeling approaches; about 2.5%.

Having a better understanding of GA methods and diffusion implementation in software algorithms, different general geometrical principles of the audience area modeling were tested to address the above-highlighted problems.

The results obtained by three different software and the different audience area geometrical simplifications are presented below. Average values in octave-bands are placed side by side to the values in the receiver positions at 1kHz.

The number representing the software from the first part of the research remained unchanged.

6.1 Method

Five different general principles of the audience area geometrical simplifications were modeled:

1 - A horizontal box, 0.9m above the floor surface;
2 - A horizontal box, 0.45m above the floor surface;
3 - Angled planes representing rows of seating, 0.2-0.9m above the floor surface;
4 - Vertical planes representing rows of seating, 0.2-0.9m above the floor surface;
5 - Vertically extruded mesh, 0.2-0.9m above the floor surface.

The receiver positions remained 1.2m above the floor surface.

The geometrical simplifications were implemented in Low level of detail computer model of Malmö Live concert hall. The simulated results using the model in the first stage of the research have proven to be of high accuracy, while keeping the computational time reasonably low.

The models were individually 'tuned' repeating the Step 4 in the procedure described in section 4.3.

Areas of the audience area as a material and its absorption properties used in different geometrical simplifications are presented in table 6.1. Scattering coefficient remained as presented in section 4.2.3.

Table 6.1: Area and absorption coefficient in five different audience area geometrical simplifications.

Audience area geometrical simplification	Surface area[m^2]	Absorption coefficient
1	1195.6	< 69 71 79 86 88 78 >
2	1075.4	< 77 80 88 94 96 83 >
3	1316.2	< 61 64 82 96 98 78 >
4	1292.5	< 63 65 74 83 85 72 >
5	1305.6	< 60 64 82 97 99 78 >

The geometrical simplifications can be seen in figure D.1.

6.2 Results

6.2.1 T30

High precision of the 'tuning' process can be seen in average T30 as well as values over receiver positions.

It can also be seen, that the coherence of the measured and the simulated values is decreasing with the geometrical complexity of the model. A high number of small surfaces requires a higher number of rays for a stable result.

When the rows of seating are geometrically represented in a model, the exact position of the receiver in relation to vertical or angled plane is important, and it is understood to be the main reason for fluctuation in T30 values in same receiver positions.

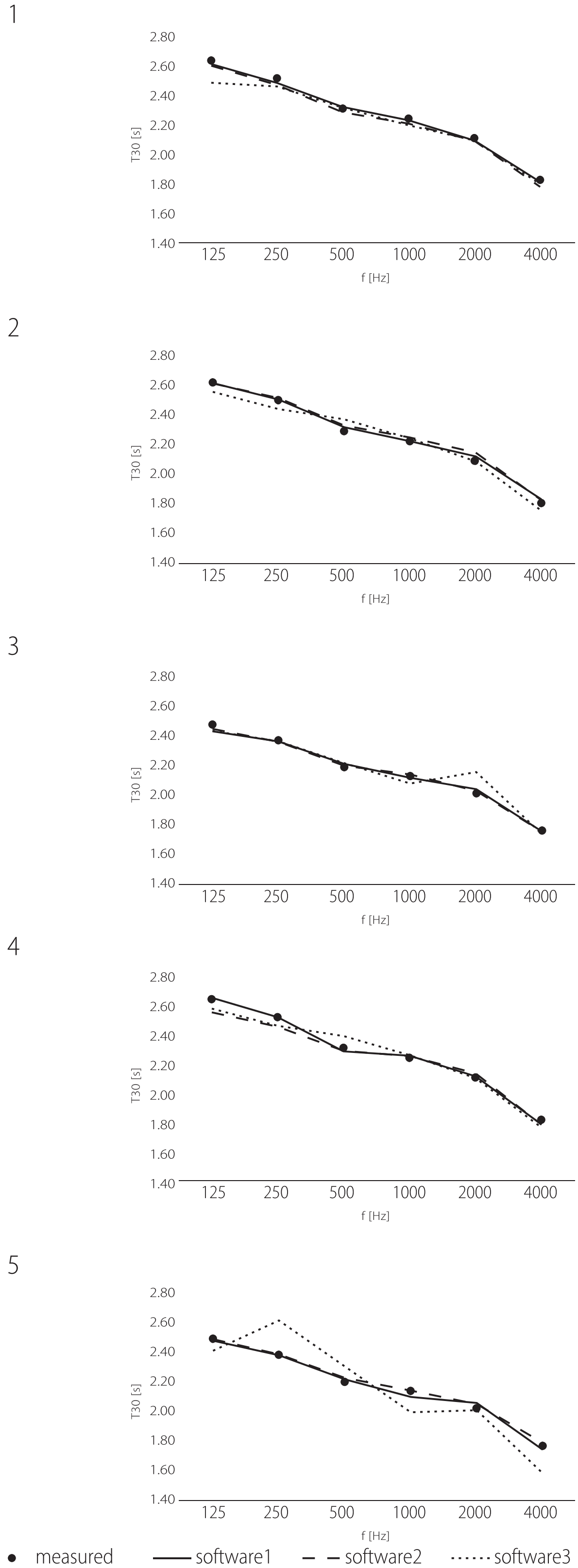

Figure 6.1: Measured and simulated values of T30[s] in octave-bands[Hz] obtained by three software and five different audience area geometrical simplifications in the model with Low level of detail of Malmö Live concert hall, Malmö.

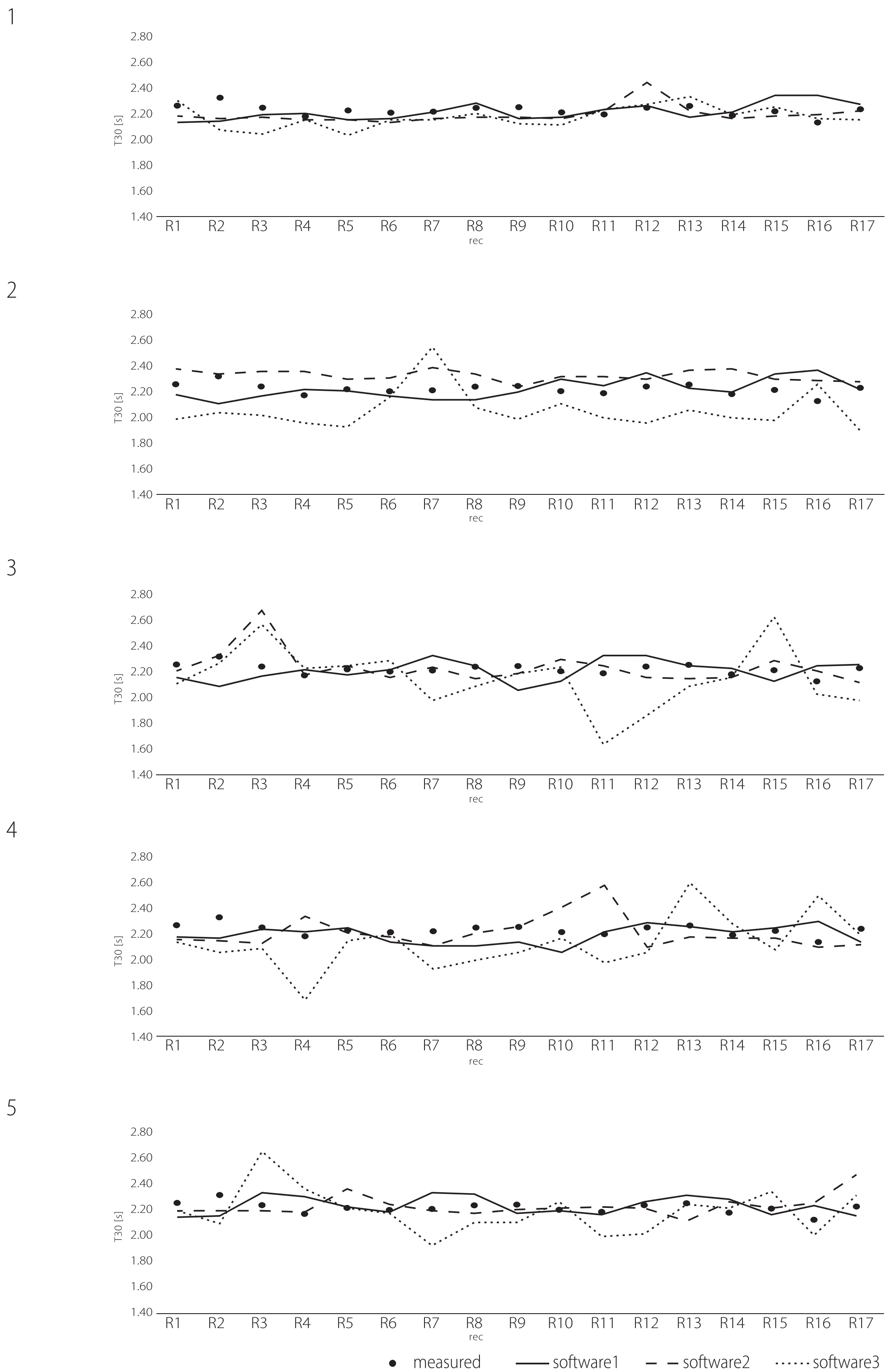

Figure 6.2: Measured and simulated values of T30[s] over 17 receiver positions at 1kHz obtained by three software and five different audience area geometrical simplifications in the model with Low level of detail of Malmö Live concert hall, Malmö.

6.2.2 C80

A good correlation between the measured and the simulated average C80 can be seen in figure 6.3 in mid-frequency bands, decreasing lower and higher in frequency spectrum. The effect of the geometrical simplification of the audience area or software algorithm on the simulated results is very small.

A closer look at C80 at 1kHz gives a better understanding of the effect of the five different modeling simplifications on the simulated results. The receiver positions can be divided into two groups; receivers in front stalls, from 1 to 6, and receivers in back stalls and balconies, from 7 to 17. The modeling principles that simplifying the audience area with horizontal plane result in overestimation of the parameter values at receiver positions in the first group, due to the problematic strong first reflection. The principals using angled or vertical planes result in underestimation of the parameter value at these positions. With the increased distance from the source, the differences in results obtained by different models decrease.

Comparison of the results obtained by the models with 1st and 2nd simplification principle, the effect of the lowered horizontal surface is apparent; the delay of the problematic reflection results in more accurate parameter prediction.

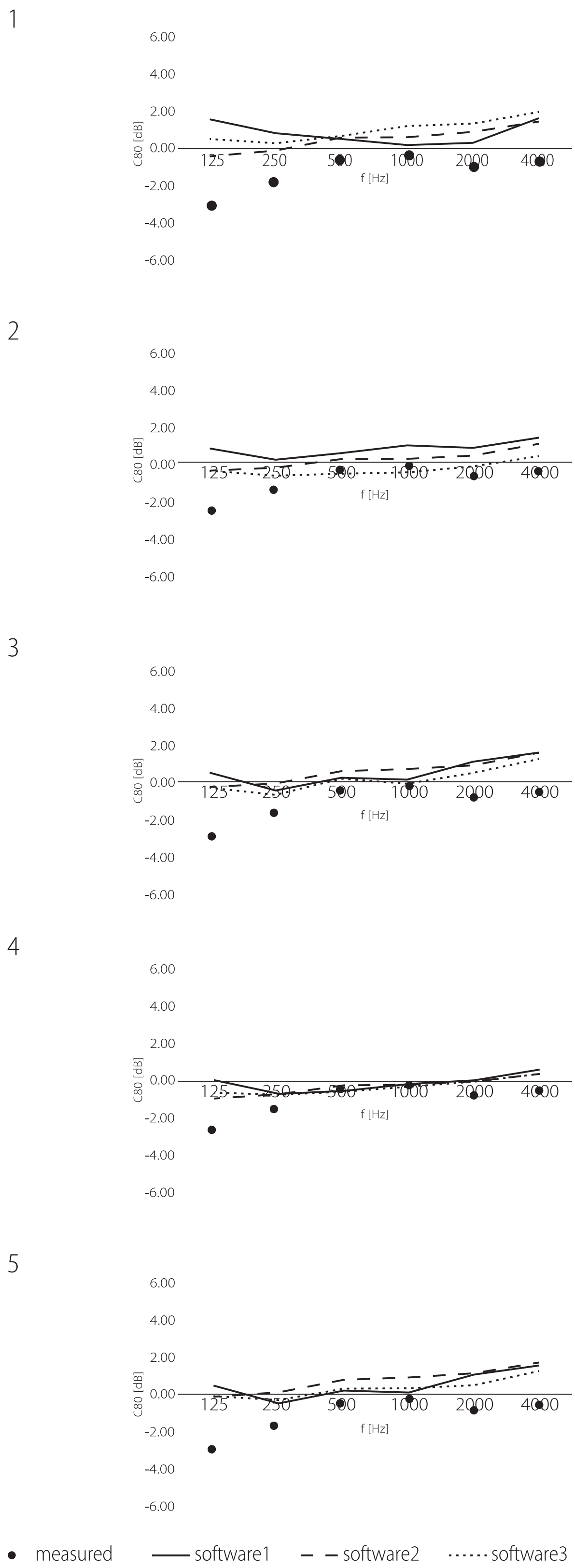

Figure 6.3: Measured and simulated values of C80[dB] in octave-bands[Hz] obtained by three software and five different audience area geometrical simplifications in the model with Low level of detail of Malmö Live concert hall, Malmö.

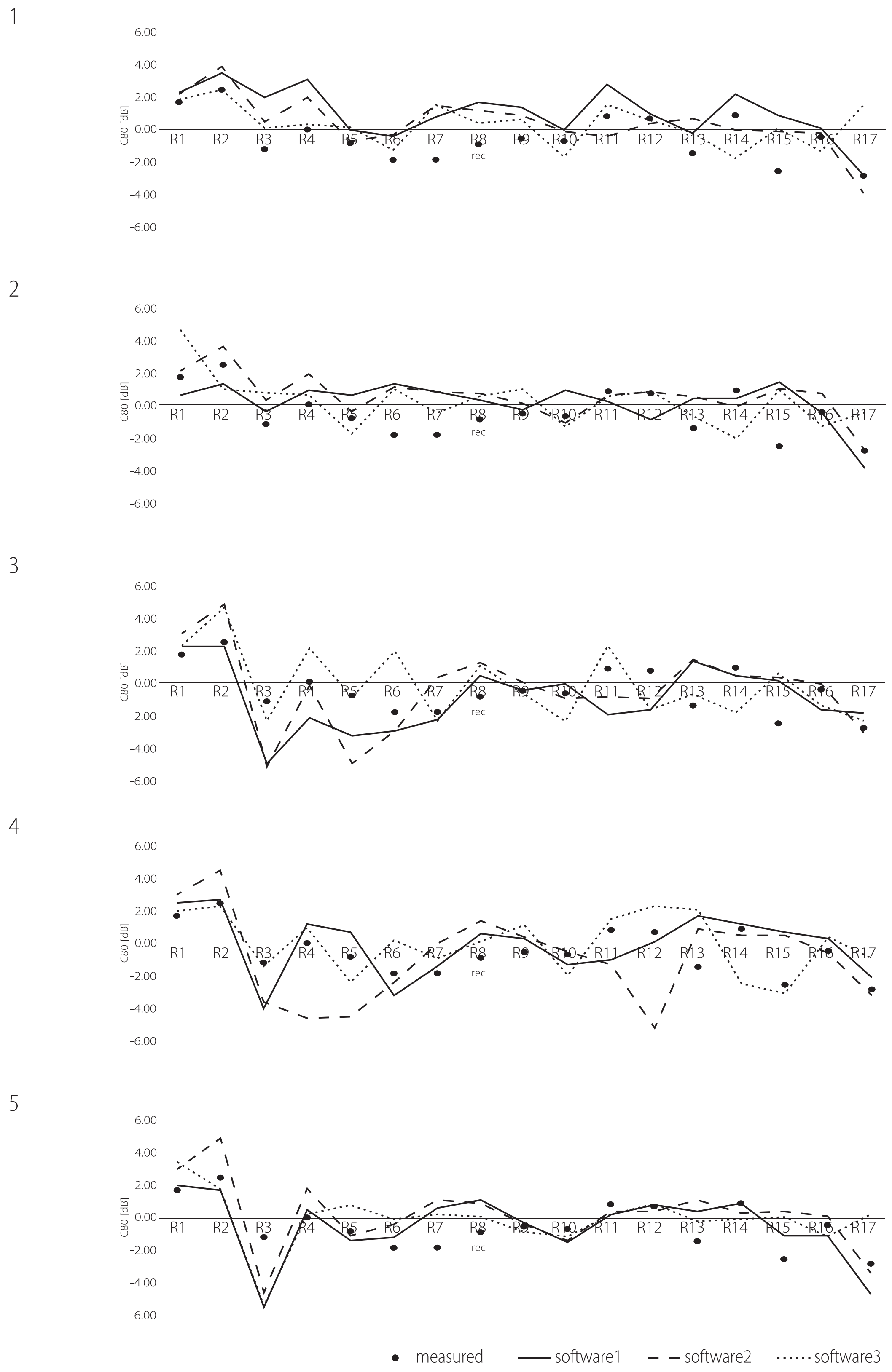

Figure 6.4: Measured and simulated values of C80[dB] over 17 receiver positions at 1kHz obtained by three software and five different audience area geometrical simplifications in the model with Low level of detail of Malmö Live concert hall, Malmö.

6.2.3 EDT and LF

The delay or geometrical redirection of the first reflection from the audience area surface does reflect in the better coherence of the measured and the simulated EDT.

The way of geometrical simplification of the audience area mainly affects the first reflection from bellow and not the lateral sound arrival; the changes are not reflected in average LF values as shown in figure 6.6.

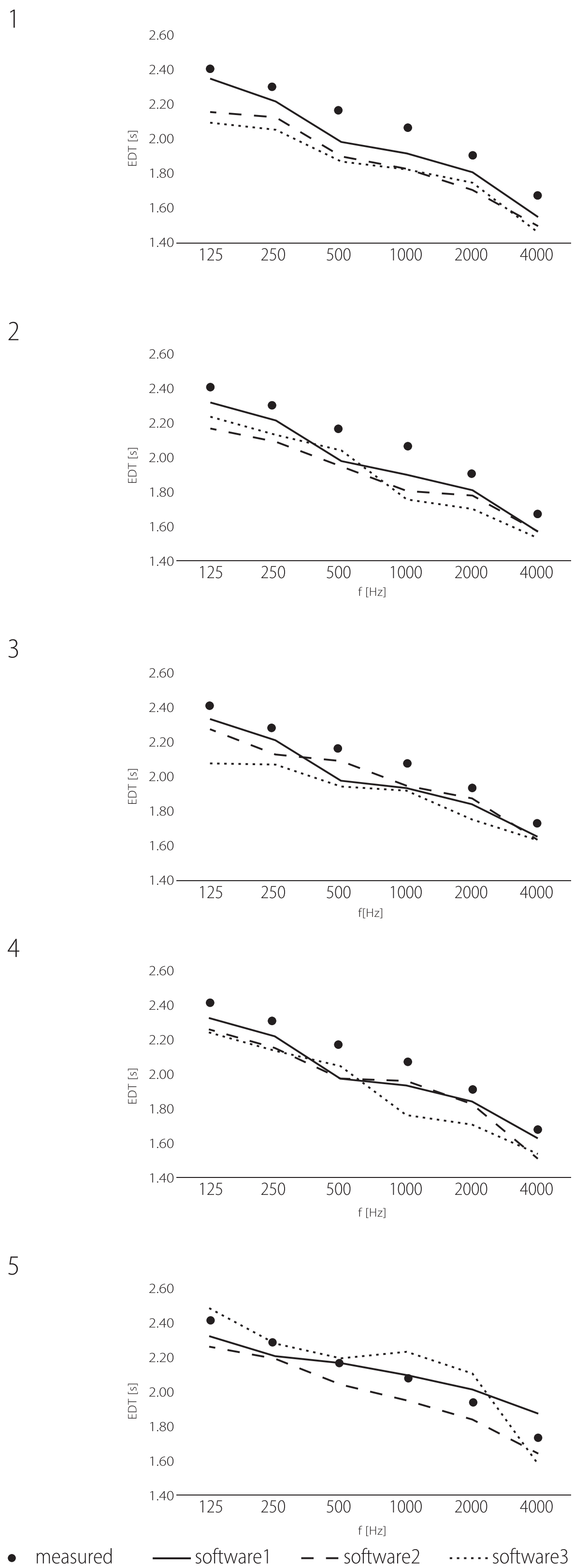

Figure 6.5: Measured and simulated average values of EDT[s] in octave-bands[Hz] obtained by three software and five different audience area geometrical simplifications in the model with Low level of detail of Malmö Live concert hall, Malmö.

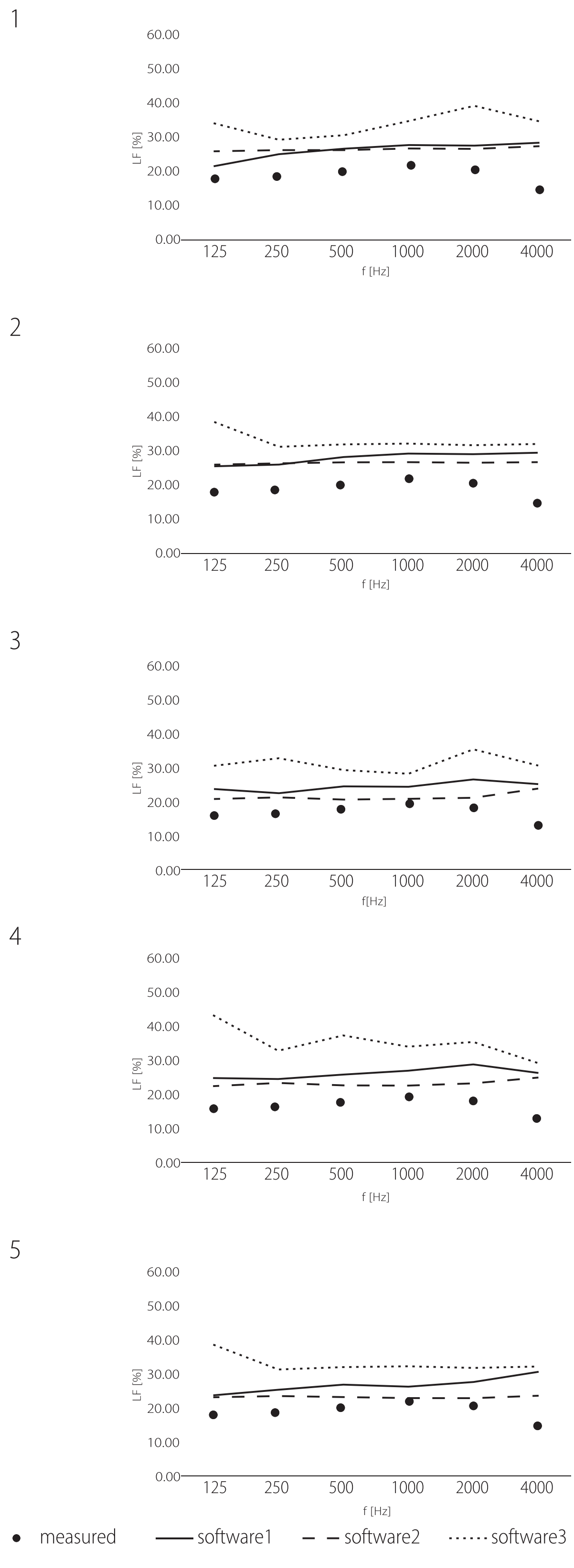

Figure 6.6: Measured and simulated average values of LF[%] in octave-bands[Hz] obtained by three software and five different audience area geometrical simplifications in the model with Low level of detail of Malmö Live concert hall, Malmö.

7. Conclusion

Room Acoustic Simulation Software is frequently used to predict characteristics of the acoustic environment in a room during a design process. The comparative research aimed to give guidelines to enable critical evaluation of the simulated results. Three software packages that are commonly used by the practitioners in the field were included; CATT v8.0, CATT v9.0, and Odeon. The research focused on three areas, understood to be the primary factors influencing the results: implementation of Geometrical Acoustics methods in software algorithms, level of detail in the computer model and geometrical simplification of the audience area.

The simulated results were compared to the measured in three existing large rooms; Grosse Muzikverein in Vienna, Malmö Live concert hall in Malmö and Norconsult AB Canteen in Göteborg.

The results of the past research have concluded that the basic Geometrical Acoustics methods implemented in the software algorithm do not have a significant influence on the simulated results as long as the algorithms also implement diffusion and scattering [12]. As these properties of sound propagation are implemented in all the software of interest in this comparative research, the more detailed analysis has focused more on the limitations of the algorithms.

The different ways to determine the early energy when the direct sound path is cut-off by geometrical elements do not result in high deviation of results.

The clear understanding of the early sound behavior results in accurate predictions not depending on the Geometrical Acoustics method implemented in the software algorithm. The inaccuracies arise in rectangular rooms with reflective surfaces. The predetermined specular reflections intensify the flutter-echo effect. The algorithms implementing the angle reflections which are rarely perfectly specular do avoid the error. Consequently resulting in more accurate results. The apparent advantage of these algorithms is also a better correlation between visually assessed and in simulation assigned scattering properties for smooth material surfaces. Therefore more friendly to the inexperienced user.

The low-frequency limitation of Geometrical Acoustics is enabling the accurate predictions of the frequencies close to the modal behavior of the room. This limits apply to low-frequency bands in large rooms and can be very limiting when simulating acoustic properties in smaller room volumes. Extending the algorithm with other methods which do not neglect the phase nature of the sound propagation, such as

Finite Element Method FEM and or Boundary Element Method BEM, would result in more accurate results.

Three levels of detail in computer model were used to test the effect of model detailing on simulated results. The geometry simplification is in many circumstances unavoidable; organic or circular shapes have to be fragmented into small surfaces to allow the simulation of the ray/particle reflection. In other cases, the geometrically fragmented orthogonal elements can be simplified and represented with higher scattering coefficient applied as a property of the material.

The highly detailed geometry does have a significant effect on the prediction of the early part of the echogram. It enables the detection of image sources and results in faster energy decay in a room.

However, the error due to the highly geometrically complex models is proven subtle in comparison to the error due to the complexity and poor understanding of highly frequency dependent scattering process. Therefore it is suggested, that the diffusive elements are modeled, taking into account that the detailing in the model requires a higher number of rays and consequently longer calculation time. The more detailed modeling was proven beneficial especially for detailed prediction in specific receiver positions.

Audience area modeling was considered as another parameter influencing the simulated results. The research concluded that the current approach of low audience area surface has been proven to provide the most reliable simulation results.

The arising question is: should the simulations be evaluated as an image of reality. However, the primary objective and most common use of the software is to simulate the room environment before it is built. And a clear understanding of its limitations helps with critical interpretation of the results.

Finally, the simulated results after the 'calibration' process were scarcely in the limit of JND for particular parameters and no software could evaluate the quality of the sound environment, where not just values, but also relationships are essential. And the human ear is the finest and most delicate critic.

Bibliography

[1] Hak, C.C.J.M. (2012) Measuring Room Impulse Responses: Impact of the Decay Range on Derived Room Acoustic Parameters. Acta Acustica united with Acustica, Vol.98.

[2] Branek, L. (2003) Concert Halls and Opera Houses: Music, Acoustics, and Architecture. Springer-Verlag, New York.

[3] Dalenbäck, B.-I. (1992) Room acoustic prediction and auralization based on an extended image source model. J.Acoust.Soc.Am.92.

[4] Savioja, L. (2015) Overview of geometrical room acoustic modeling techniques. J.Acoust.Soc.Am.138.

[5] Funkhouser, T. (2004) A beam tracing method for interactive architectural acoustics. J.Acoust.Soc.Am.115.

[6] Nosal, E.-M. (2004) Improved algorithms and methods for room sound-field prediction by acoustical radiosity in arbitrary polyhedral rooms. J.Acoust.Soc.Am.116.

[7] Rindel, H.J. (2000) The Use of Computer Modeling in Room Acoustics. Journal of Vibroengineering, No.3.

[8] Christensen, C.L. (2015) ODEON Room Acoustics Software, Version 13, User's manual. Odeon A/S, Denmark.

[9] Dalenbäck, B.-I. (2007) CATT-Acoustic v8.0,up to and inclouding v8.0g build 2, User's manual. CATT, Gothenburg.

[10] Dalenbäck, B.-I. (2011) CATT-Acoustic v9.0, User's manual. CATT, Gothenburg.

[11] Vorländer, M. (2008) Auralization. Springer-Verlag, Berlin, Heidelberg.

[12] Vorländer, M. (1995) International Round Robin on Room Acoustical Computer Simulations. 15th International Congress on Acoustics Trondheim, Norway.

[13] Bork, I. (2000) A Comparison of Room Simulation Software - The 2nd Round Robin on Room Acoustical Computer Simulation. Acustica, Vol.68.

[14] Bork, I. (2005) Report on the 3rd Round Robin on Room Acoustical Computer Simulation - Part 1 and 2. Acta Acustica united with Acustica, Vol.91.

[15] Wang, L.M. (2004) Interactions of Model Detail Level and Scattering Coefficients in Room Acoustic Computer Simulation. Architectural Engineering - Faculty Publications, Paper 18.

[16] Howarth, M.J. (2000) An assessment of the accuracy of a hybrid room acoustics model with surface diffusion facility. Applied Acoustics, No.60.

[17] Lam, Y.W. (1995) On the Description of Partially Diffused Reflections in a Room Acoustics Computer Model. Proc. 15th ICA, Vol.4.

[18] Nagy, A.B. (2010) Room acoustical modelling differences and their consequences. Internoise, Lisbon.

[19] Choi, Y.-J. (2005) Some current issues in computer modelling for room acoustic design. Acoustics Australia, Vol.33.

A. Appendix

Table A.1: Source positions in Grosse Muzzikverein, Vienna.

Source	x	y	z	
S1	2	-2	2.24	*stage*
S2	6	-3	2.85	*stage*
S3	0.25	-7	3.36	*stage*

Table A.2: Receiver positions in Grosse Muzzikverein, Vienna.

Receiver	x	y	z	
R1	5.9	6.5	1.2	*stalls*
R2	0.25	6.5	1.2	*stalls*
R3	-5.9	6.5	1.2	*stalls*
R4	5.9	12.7	1.2	*stalls*
R5	0.25	12.7	1.2	*stalls*
R6	-5.9	12.7	1.2	*stalls*
R7	5.9	16.5	1.2	*stalls*
R8	0.25	16.5	1.2	*stalls*
R9	-5.9	16.5	1.2	*stalls*
R10	5.9	20.5	1.2	*stalls*
R11	0.25	20.5	1.2	*stalls*
R12	-5.9	20.5	1.2	*stalls*
R13	5.3	24	1.2	*stalls*
*R14**	-5.3	24	1.2	*stalls*
R15	8.4	7.8	2.2	*loge*
R16	-8.4	7.8	2.2	*loge*
R17	8.4	17.25	2.2	*loge*
R18	-8.4	17.25	2.2	*loge*
R19	7.6	4	7.2	*balcony loge*
*R20**	-7.6	4	7.2	*balcony loge*
R21	7.6	11.5	7.2	*balcony loge*
R22	-7.6	11.5	7.2	*balcony loge*
R23	7.6	19	7.2	*balcony loge*
R24	-7.6	19	7.2	*balcony loge*
R25	6	28.8	7.2	*balcony*
R26	0.25	28.8	7.2	*balcony*
R27	-6	28.8	7.2	*balcony*
R28	6	32.1	7.8	*balcony*
R29	0.25	32.1	7.8	*balcony*
R30	-6	32.1	7.8	*balcony*
R31	4.4	34	10.7	*galery*
R32	0.25	34	10.7	*galery*
R33	-4.4	34	10.7	*galery*

** the positions used in simulations only*

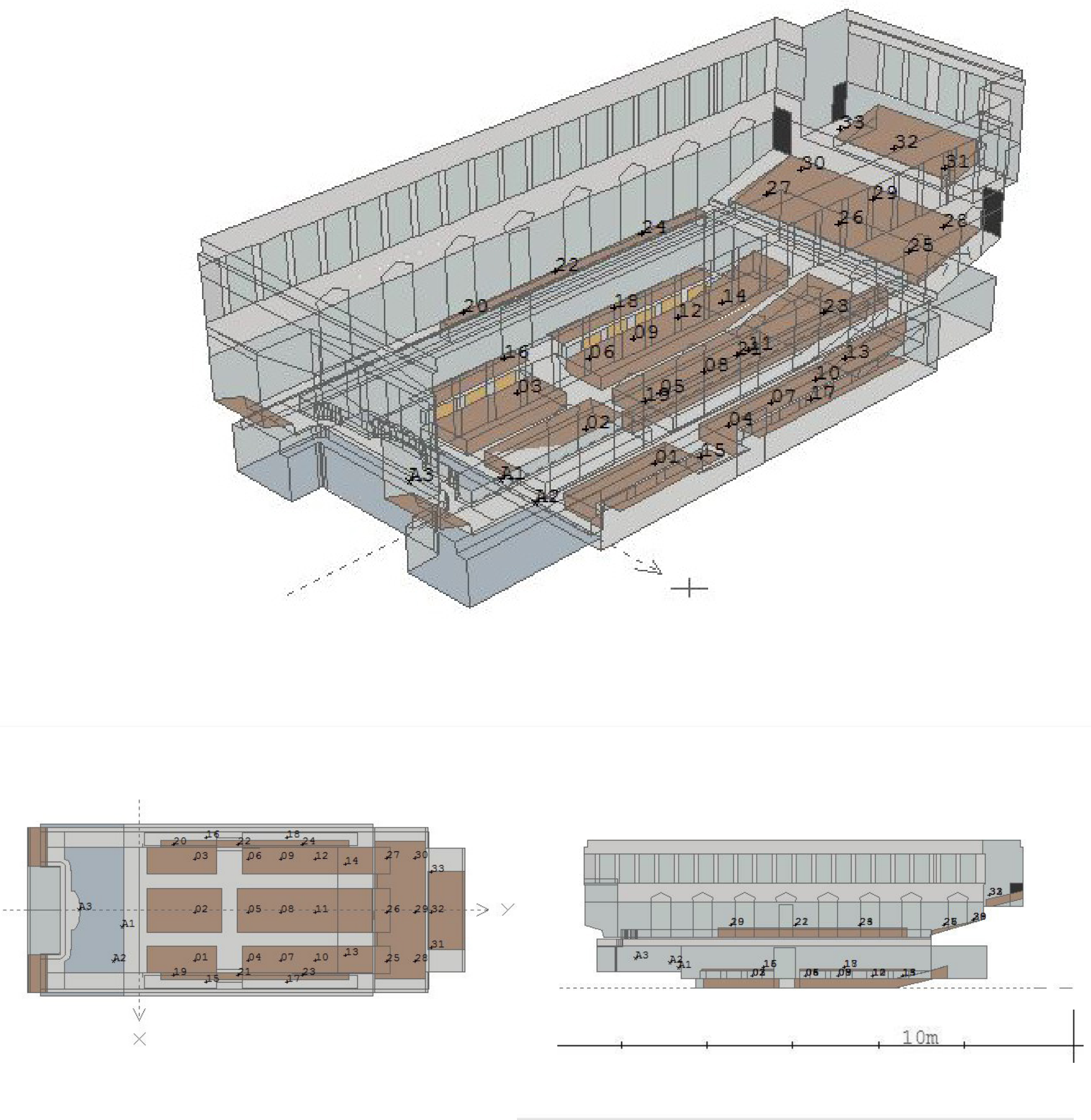

Figure A.1: Low level of detail computer model of Grosse Muzzikverein with source and receiver positions.

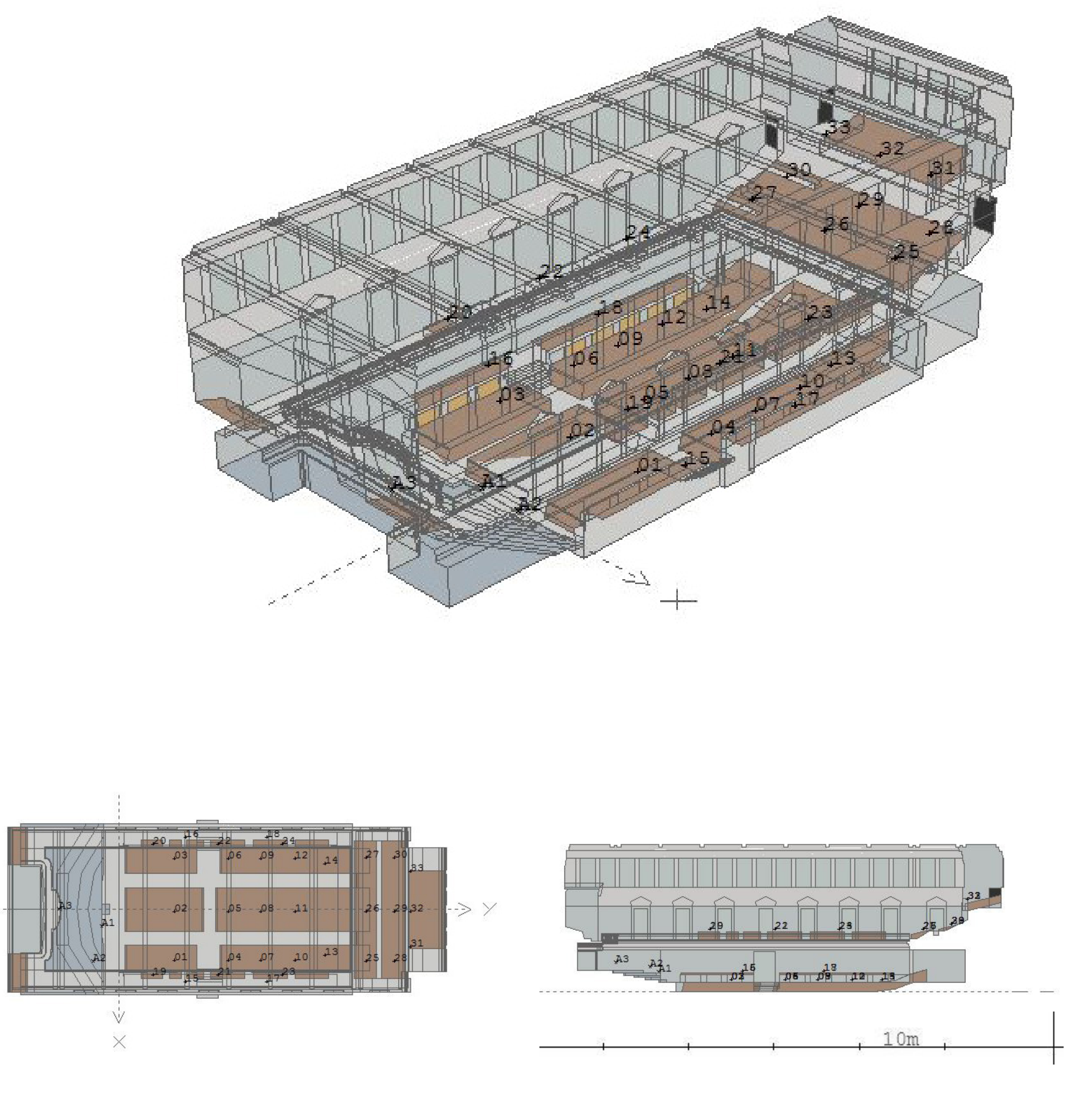

Figure A.2: Medium level of detail computer model of Grosse Muzzikverein with source and receiver positions.

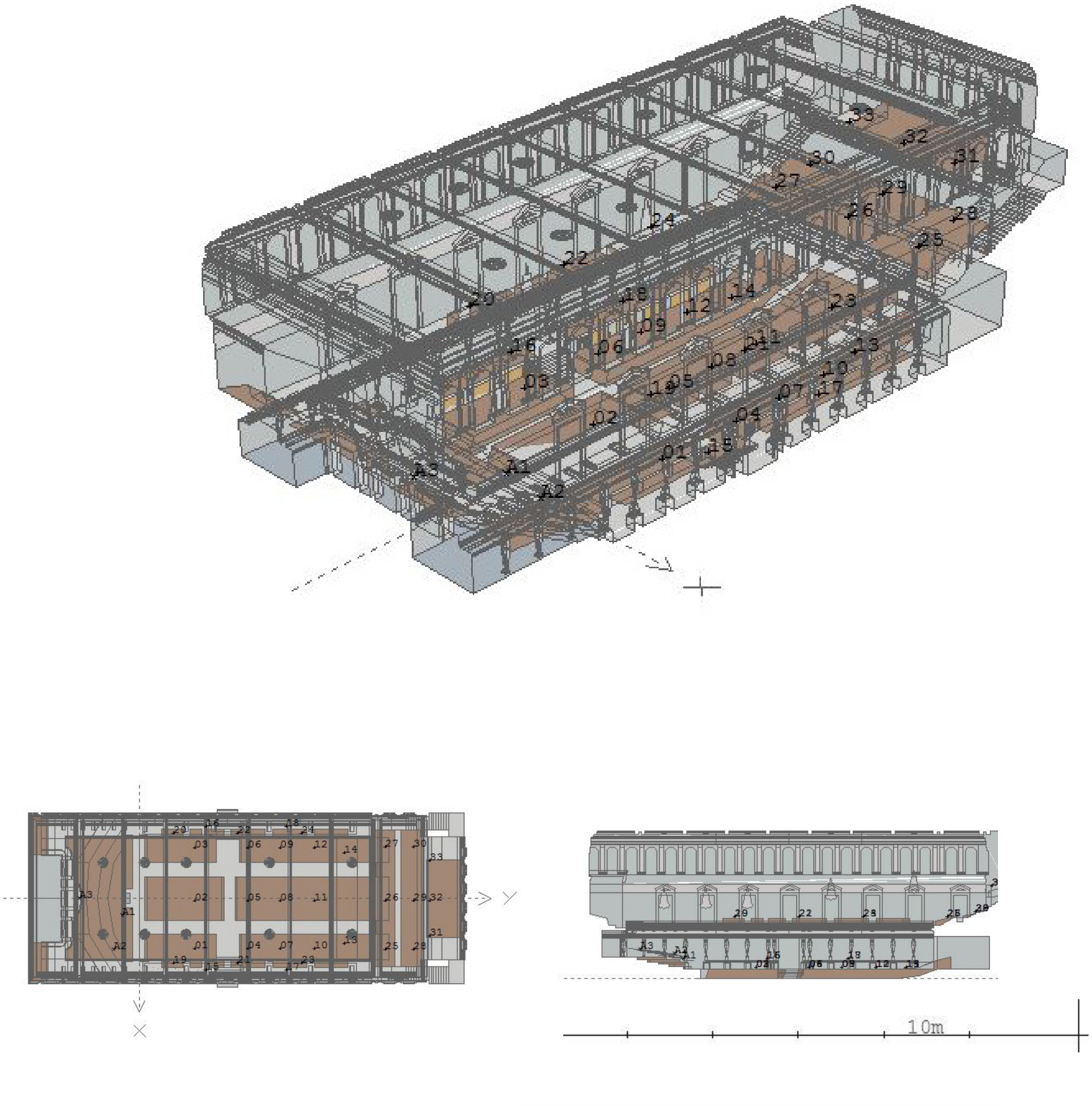

Figure A.3: High level of detail computer model of Grosse Muzzikverein with source and receiver positions.

B. Appendix

Table B.1: Source positions in Malmö Live concert hall, Malmö.

Source	x	y	z	
S1	-0.25	11.90	1.2	*stage*
S2	-0.25	5.60	2.0	*stage*

Table B.2: Receiver positions in Malmö Live concert hall, Malmö.

Receiver	x	y	z	
R1	-5.80	19.80	0.50	*stalls*
R2	-1.95	19.80	0.50	*stalls*
R3	-5.80	26.60	1.20	*stalls*
R4	-1.95	26.60	1.20	*stalls*
R5	-5.60	31.50	2.10	*stalls*
R6	-1.95	31.50	2.10	*stalls*
R7	-5.80	38.30	4.00	*1st balcony*
R8	-1.95	38.30	4.00	*1st balcony*
R9	-9.60	24.70	2.50	*1st balcony side*
R10	-9.50	31.10	3.10	*1st balcony side*
R11	-2.80	41.50	9.00	*2nd balcony*
R12	-7.50	40.30	8.90	*2nd balcony*
R13	-9.50	30.30	6.70	*2nd balcony side*
R14	-9.50	21.30	5.90	*2nd balcony side*
R15	-2.50	45.80	13.80	*3rd balcony*
R16	-6.80	45.00	13.80	*3rd balcony*
R17	-10.50	31.10	10.30	*3rd balcony side*

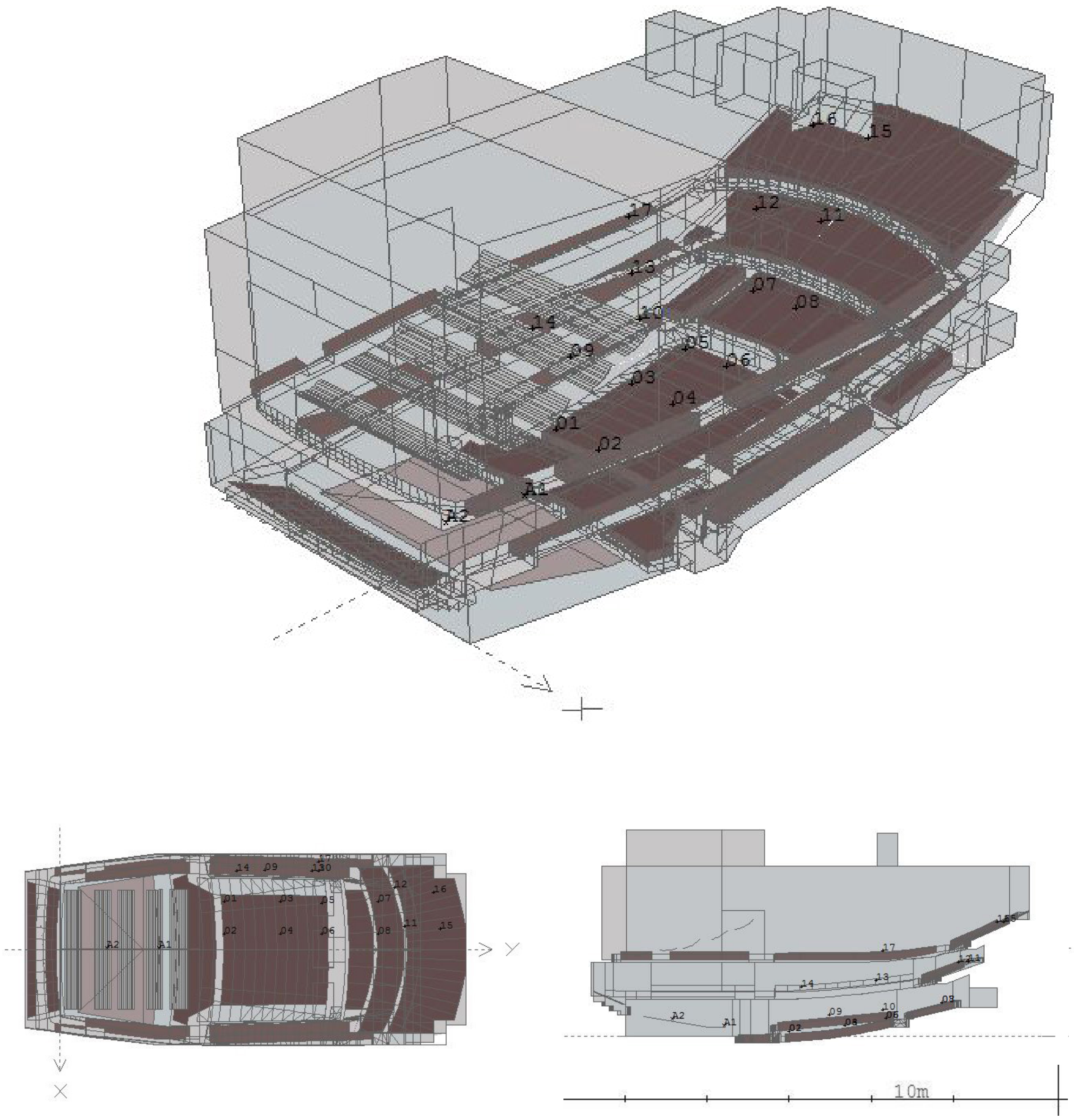

Figure B.1: Low level of detail computer model of Malmö Live concert hall with source and receiver positions.

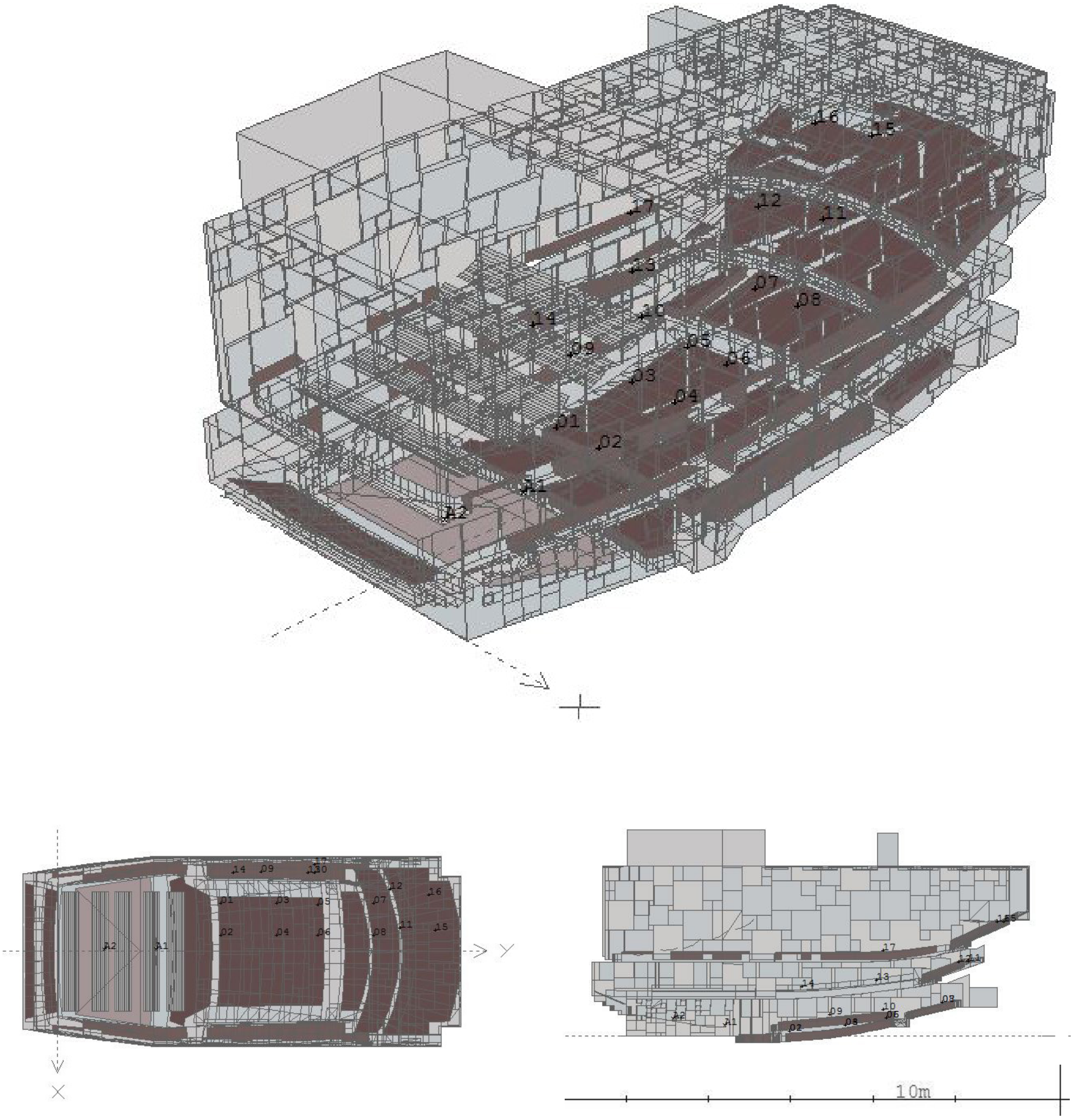

Figure B.2: Medium level of detail computer model of Malmö Live concert hall with source and receiver positions.

C. Appendix

Table C.1: Source positions in Norconsult AB Canteen, Göteborg.

Source	x	y	z
S1	4.1	5.7	1.20
S2	2.6	0.0	1.45

Table C.2: Receiver positions in Norconsult AB Canteen, Göteborg.

Receiver	x	y	z
R1	-5.9	2.3	1.2
R2	-4.1	5.7	1.2
R3	-3.5	6.6	1.2
R4	5.3	2.3	1.2
R5	4.7	3.2	1.2
R6	-1.9	3.0	1.2
R7	-0.9	5.9	1.2
R8	1.4	3.3	1.2
R9	0.9	5.9	1.2
R10	1.4	6.7	1.2

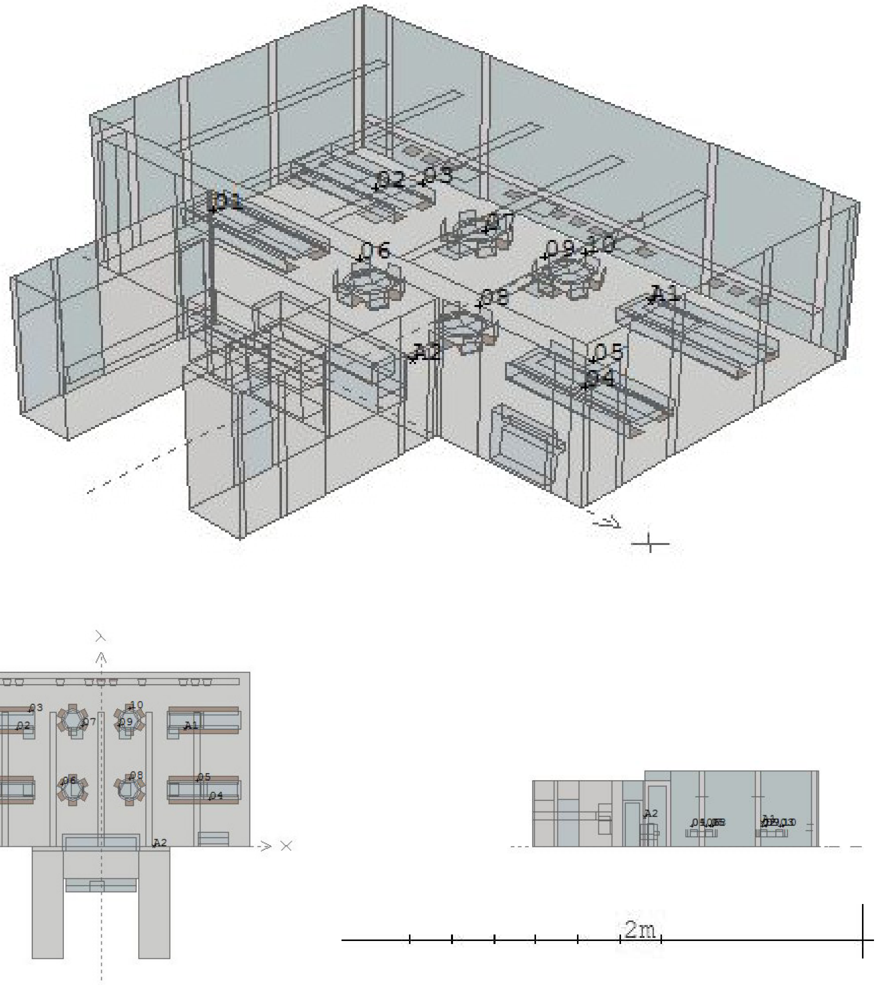

Figure C.1: High level of detail computer model of Norconsult AB Canteen with source and receiver positions.

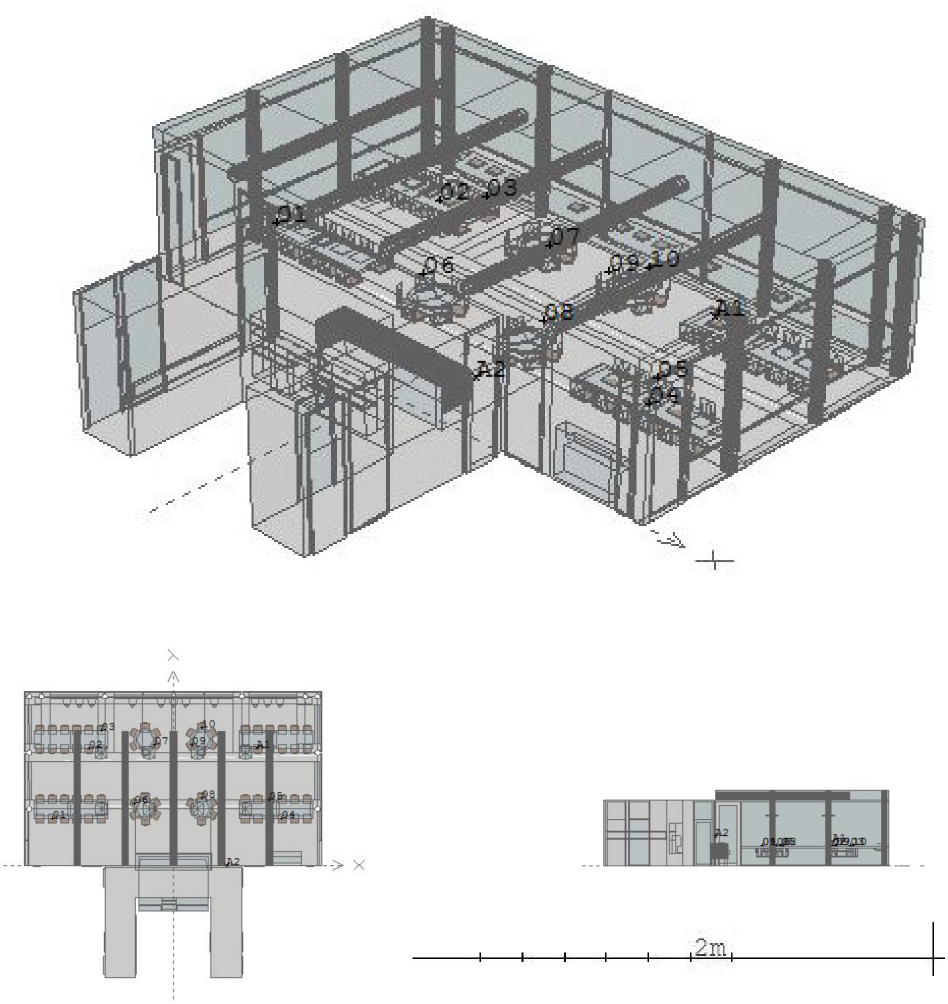

Figure C.2: Very high level of detail computer model of Norconsult AB Canteen with source and receiver positions.

D. Appendix

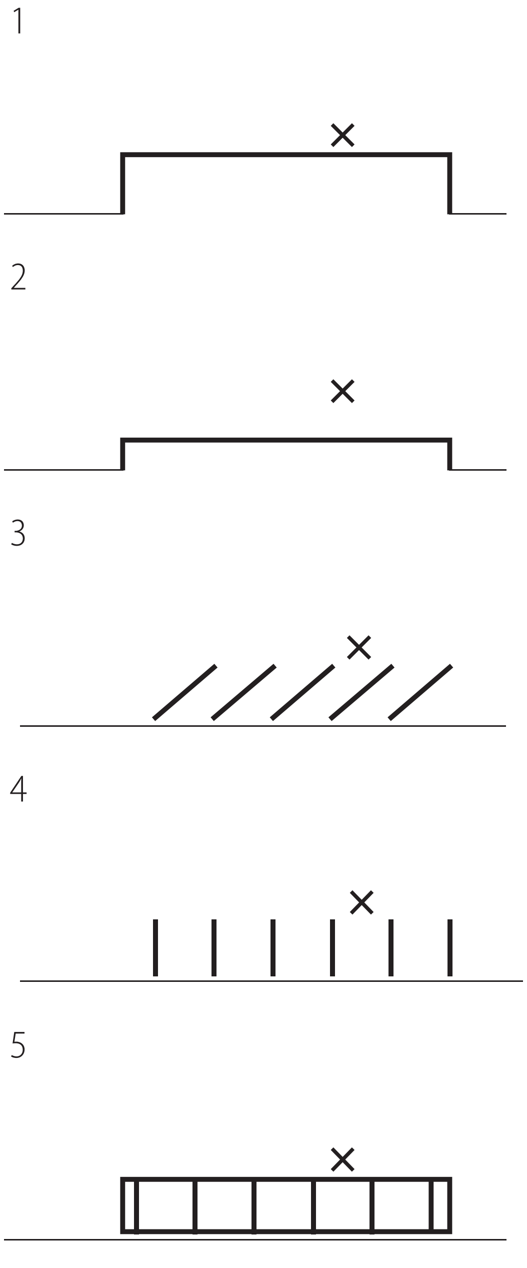

Figure D.1: Geometrical simplifications of the audience area.